



RADECS Short Course
Section 4
Radiation Hardness Assurance (RHA)
for Space Systems

Christian Poivey
SGT-Inc/NASA-GSFC

given at
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RHA Outline

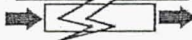
- Introduction
- Programmatic aspects of RHA
- RHA components
 - requirements and specifications
 - mission radiation environment
 - parts selection and radiation tolerance
- Analysis at the function/subsystem/system level
 - TID/DD
 - SEE
- Conclusion



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What is RHA ?

- RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their design specifications after exposure to the space radiation environment
- Deals with environment definition, part selection, part testing, spacecraft layout, radiation tolerant design, and mission/system/subsystems requirements

Radiation Hardness Assurance goes beyond the piece part level



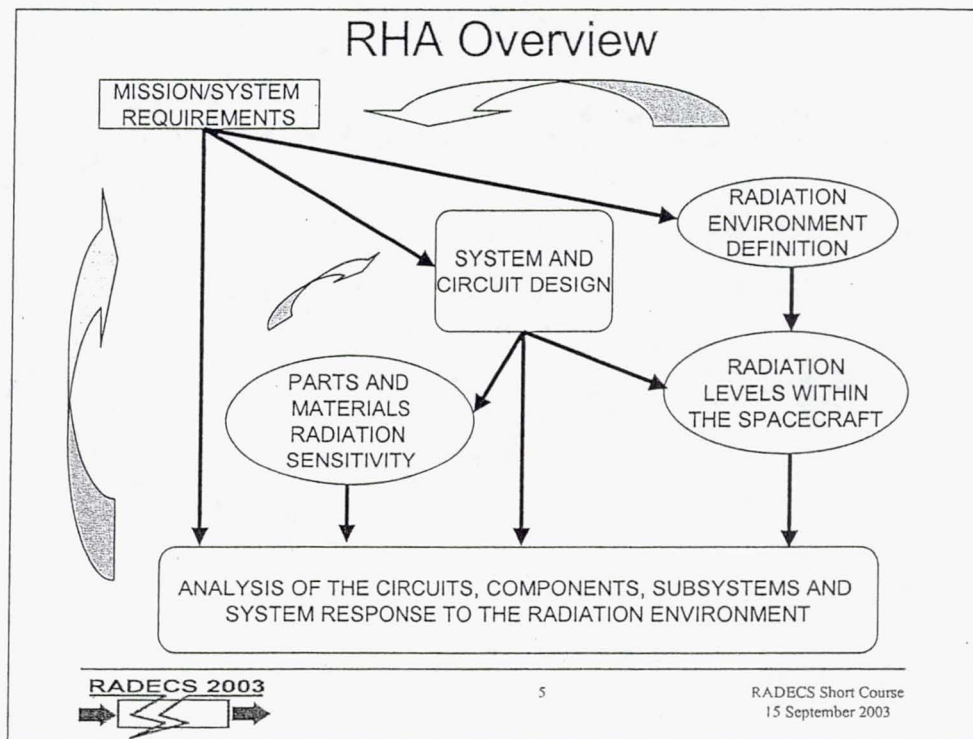
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The space radiation environment can lead to extremely harsh operating conditions for on-board electronic box and systems. As presented in the previous sections, radiation accelerates the aging of electronic parts and materials and can lead to a degradation of electrical performance; it can also create transient phenomena on parts. Such damage at the part level can induce damage or functional failure at electronic box, subsystem, and systems levels.

A rigorous methodology is needed to ensure that the radiation environment does not compromise the functionality and performance of system life. This methodology is called hardness assurance. It consists of those activities undertaken to ensure that the electronic piece parts placed in the space system perform to their design specification to the space environment. It deals with system requirements, environmental definition, parts selection, part testing, shielding, and radiation tolerant design. All these elements should play together to produce a system tolerant to the radiation environment.

RHA is therefore not limited to piece-part level, but this level plays an important role.



The slide shows an overview of the radiation hardness assurance process. The main steps are:

- Definition of the environment
 - External to the spacecraft
 - Internal to the spacecraft
- Development of specifications based on criticality factors
- Definition of parts and materials radiation sensitivity
 - Use of existing data
 - Testing
- Evaluation of the design/components
 - Development of mitigation approaches

This process is iterative. It starts first with top level estimations of the radiation environment. Then the radiation levels are refined, and the electronic designs analyzed to validate the use of the most sensitive parts.

Hardness Assurance procedures

- US MIL handbooks MIL-HDBK
 - 814- Ionizing dose and neutron HA guidelines for microcircuits and semiconductor devices, 1994.
 - 816- Guidelines for developing RHA device specifications, 1994 updated in 2002.
 - 817- System development RHA, 1994.



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One the main challenges at the piece-part level is the variability of the response to radiation of non hardened parts. To solve this problem the US has developed "Hardness Assurance Procedures". Some of them are relevant for space systems. The key activity of these procedures is the identification of microcircuits which require the most careful monitoring to ensure they meet their design specifications. This activity is known as categorization. It is the process by which the radiation hardness of a device is compared to the radiation specification and a decision is made concerning the requirement for monitoring the hardness of those devices placed in the system.

Challenges of Space Systems and COTS

- Space Systems
 - Requirement for high probability of survival
 - Small number of systems, sometimes one
 - Many part types, small buys of each part type
 - Use of complex, state-of-the-art parts
 - Use of commercial off-the-shelf (COTS)
- COTS
 - No configuration control
 - Obsolescence
 - Often no radiation data in databases
 - Often only available in plastic



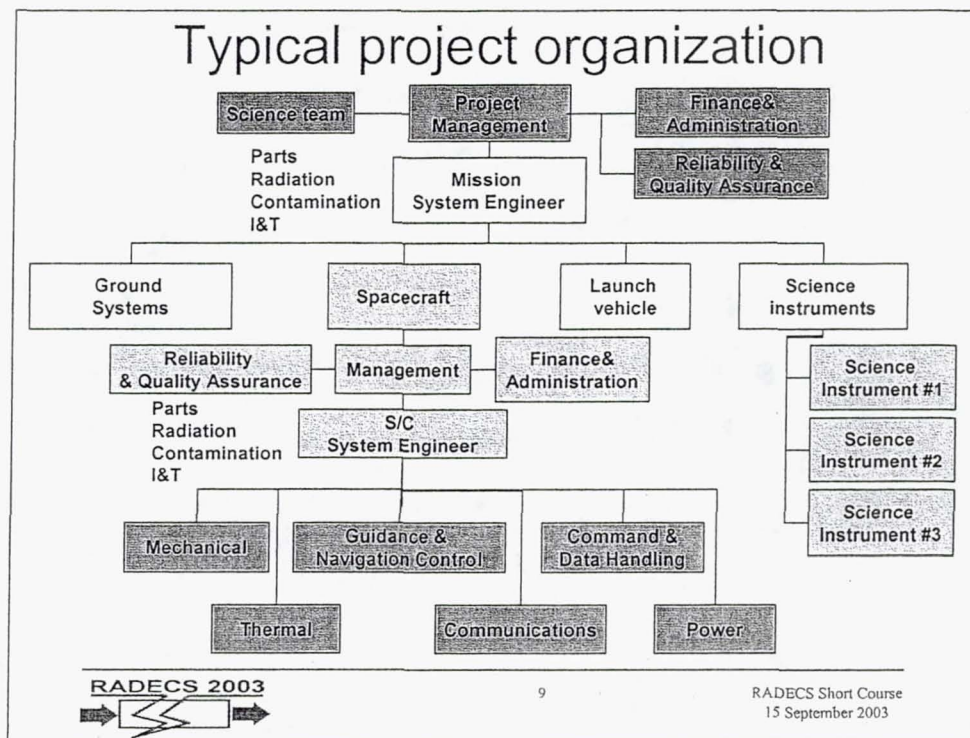
However space systems pose specific challenges to the traditional characterization and categorization schemes. In a traditional approach, a design hardening is performed and RHA is applied during the production phases to guarantee that design hardening is not compromised. In space system, there is generally a small number of systems, sometimes one, and the design hardening is performed concurrently with the design hardening.

The use of Commercial Of The Shelf (COTS) parts in space systems is one the main challenges. COTS parts shows a very large difference in radiation response, both for TID and SEE, between manufacturers. Very large differences may also be observed from lot to to lot for a same part from the same manufacturer. The traceability is also very difficult, datecode information, when available, does not guarantee the same wafer lot. Some vendors use multiple fabrication foundries and more than one foundry could be included in the date code lot. Packaging is also important because it may play a significant role in radiation tolerance.

Traditional RHA approaches may be used but with some modifications to deal with these challenges. For example, as mentioned before, qualification and lot acceptance are often the same. If this is not the case every COTS procurement lot should be tested independently of the radiation design margin for this specific part. A particular attention should be also paid to test exactly what is flown: same package and same preconditioning.

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This slide shows a typical project organization. It follows the breakdown in different systems and science instruments and then the breakdown of each system in different subsystems.

Radiation engineering is managed at the system engineering level like other specialty engineering disciplines. Each subsystem is a system by itself and the radiation hardness assurance of the subsystem can be managed at this level based on RHA specifications coming from the upper level.

Sensible RHA Programmatics A Two-Pronged Approach

- Lead radiation PROJECT engineer
 - Integrate radiation like other engineering disciplines
 - Parts, thermal,...
 - Single point of contact for all radiation issues
 - Environment, parts evaluation, testing,...
- Follow a systematic approach to RHA
 - RHA active early in program reduces cost in the long run
 - Issues discovered late in programs can be expensive and stressful
- Mission requirements and philosophies vary to ensure mission performance
 - What works for a shuttle mission may not apply to a deep-space mission



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There are many ways of managing the process of hardness assurance. At NASA, the subsystem leads are responsible for all environment constraints. And the system engineer is responsible of the constraints at the system level. There is one project lead radiation engineer who is part of the project team and integrate radiation like other disciplines (thermal, parts...). He is the single point of contact for all radiation issues:

- definition the radiation environment and the project hardness assurance requirement at the beginning of the project.
- Identification of all the radiation sensitive parts, testing, and provides the data to the design engineers.
- shielding analysis
- designers support to implement radiation tolerant designs

A systematic approach to RHA starting early in the program life reduces cost in the long run. Issues discovered late in the program can be expensive and stressful.

Typical project life cycle

- Pre phase A – advanced studies
 - Mission Concept Review
- Phase A – Preliminary analysis
 - Mission Definition Review
- Phase B – Definition
 - System Requirements Review
 - System Definition Review
 - System Preliminary Design Review
 - Lower level Preliminary Design Reviews
- Phase C – Design
 - Subsystem (and lower level) Critical Design Reviews
 - System Critical Design Review
- Phase D – Development
 - Test Readiness Reviews (all levels)
 - System Acceptance Review
 - Flight Readiness Review
 - Operational Readiness Review
- Phase E - Operations



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The project life cycle consists of everything that should be done to accomplish a project into distinct phases separated by control gates, the reviews. The project can not advance from one phase to the next one if the reviews are not successful.

The purpose of pre phase A studies is to produce ideas for new missions. The control gates are the Mission Concept Review and informal proposal reviews.

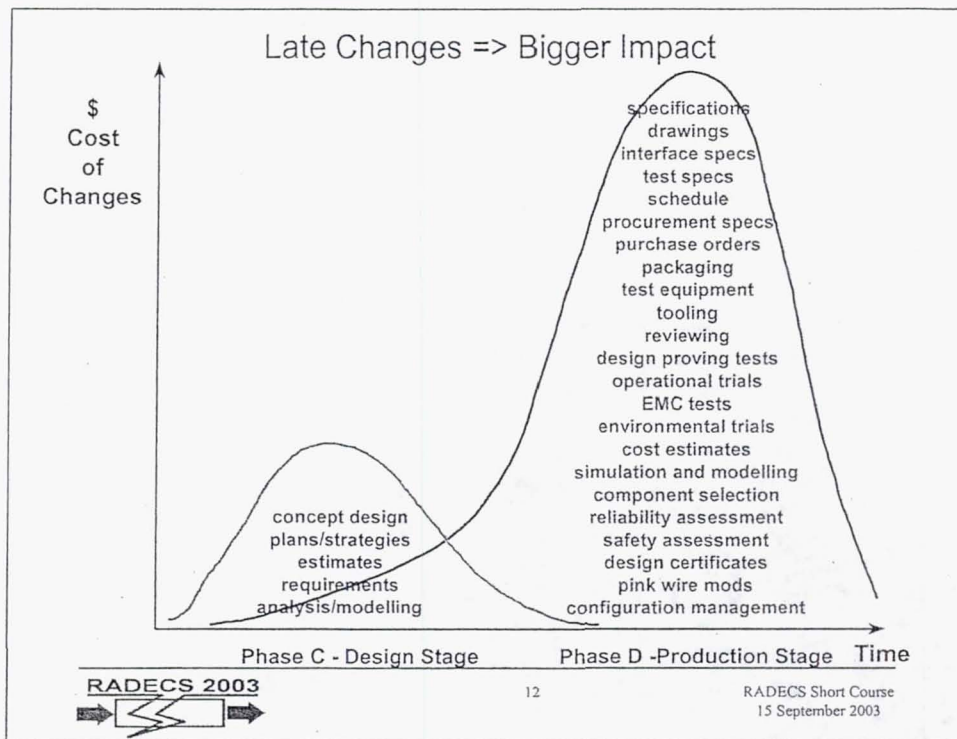
The purpose of phase A analysis is to determine the feasibility of a suggested new system and its compatibility with strategic plans. Mission top level requirements and operations concepts are developed during this phase. The main control gate is the Mission Definition Review.

The purpose of the phase B is to establish an initial project baseline which includes a formal flow down of the project level performance requirements to a complete set of systems and subsystem design specifications for both flight and ground elements and corresponding preliminary designs. System functional performance requirements along with architectures and designs become firm as system trades and subsystems trades iterate back and forth in the effort to seek the more cost effective designs. Control gates are the System Requirement Reviews, the System Definition Review, the System level Preliminary Design Review, and the lower level Preliminary Design Reviews. From this point, almost all changes to the baseline are expected to represent successive refinements, not fundamental changes.

The purpose of phase C is to establish a complete design ("built to" baseline) that is ready to fabricate, integrate, and verify. Trade studies continue. Engineering test units more closely resembling actual hardware are built and tested so as to establish confidence that the design will function in the expected environments. Engineering specialty analysis (including radiation effects) results are integrated in the design, and the manufacturing process and controls are defined and validated. Phase C culminates in a series of Critical Design Reviews containing the system level CDR and CDRs corresponding to the different levels of the system hierarchy. The CDR is held prior the start of fabrication/production.

The purpose of phase D is to built and verify the system designed in the previous phase, deploy it, and prepare for operations. The major product is a system that has been shown to be capable of accomplishing the purpose for which it was created. The control gates are the Test Readiness Reviews (at all levels), the System Acceptance Review, the Flight Readiness Review, and the Operational Readiness Review.

The products of the Phase E are the results of the mission.



As already mentioned, it is critical to consider RHA as the product of continuum activities. Without proper attention from the beginning of the program, the activity will not be able to successfully assure of the system. Too often, RHA is a set of tasks appended to the end of a program to meet a documentation requirement. Without forethought, RHA is unlikely to be program or cost effective. As seen in this slide, the cost and schedule impact of a change due to late discovery of a radiation problem is important.

Radiation Hardness Assurance During the Program Life

- Pre Phase A, Phase A
 - Draft environment definition
 - Draft hardness assurance requirements (top level)
 - Preliminary studies
- Phase B - PDRs
 - Final environment definition
 - Electronic design approach
 - Preliminary spacecraft layout for shielding analysis
 - Preliminary shielding analysis & hardness assurance requirements update
- Phase C -CDRs
 - Radiation test results
 - Final shielding analysis & final hardness assurance requirement
 - Circuit design analysis results
- Phase D
 - Radiation Lot Acceptance Tests (RLAT)
- Phase E
 - Failure analysis



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This chart shows the different milestones of RHA during a program life:

- during the proposal/feasability phases (Pre Phase A, Phase A):
 - the radiation environment is defined. This allows to estimate the effort that will need to be put in RHA in this program.
 - The hardness requirements are defined (top level requirements)
 - and preliminary studies are performed. For example, a preliminary testing of a key device, for example a detector, for the mission success.
- At the end of phase B, for the PDRs, the environment definition is generally finalized. The electronic design approach is defined, the most critical parts are chosen. A preliminary spacecraft layout has allowed to perform a preliminary shielding analysis and then define more accurate top level requirements. Then the radiation requirements are updated.
- At the end of Phase C, for the CDRs, all the radiation test results are available, the final shielding analysis has been performed and circuits design analysis results are available.
- In phase D, most of the radiation hardness assurance is done. The main activity is the test of flight lots.
- During operations, in case of failure, the radiation lead is part of the failure analysis team. In case of a radiation induced failure, the understanding of the failure will help to find functional solution for the ground operations.

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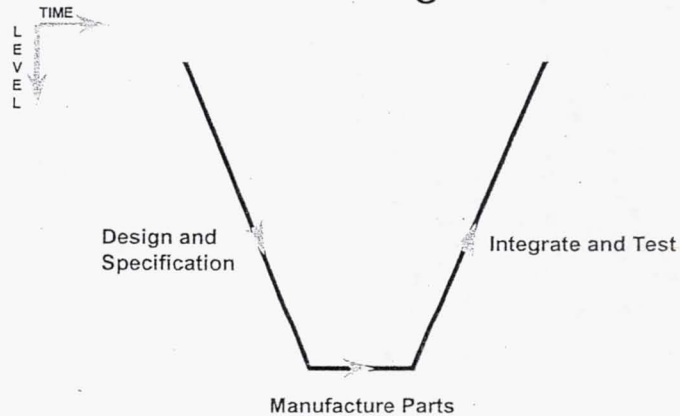


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We have seen that a large number of people, factors and considerations go into a system design. For example a subsystem could decide to add some shielding to reduce the radiation levels, this could be in conflict with the subsystems and the total system weight requirements. The arrangements for resolving conflicts are contained in a series of project documents: the **specifications**. The compliance to these requirements is checked during the reviews.

System engineering – The 'V' Diagram



After NASA Systems Engineering Handbook



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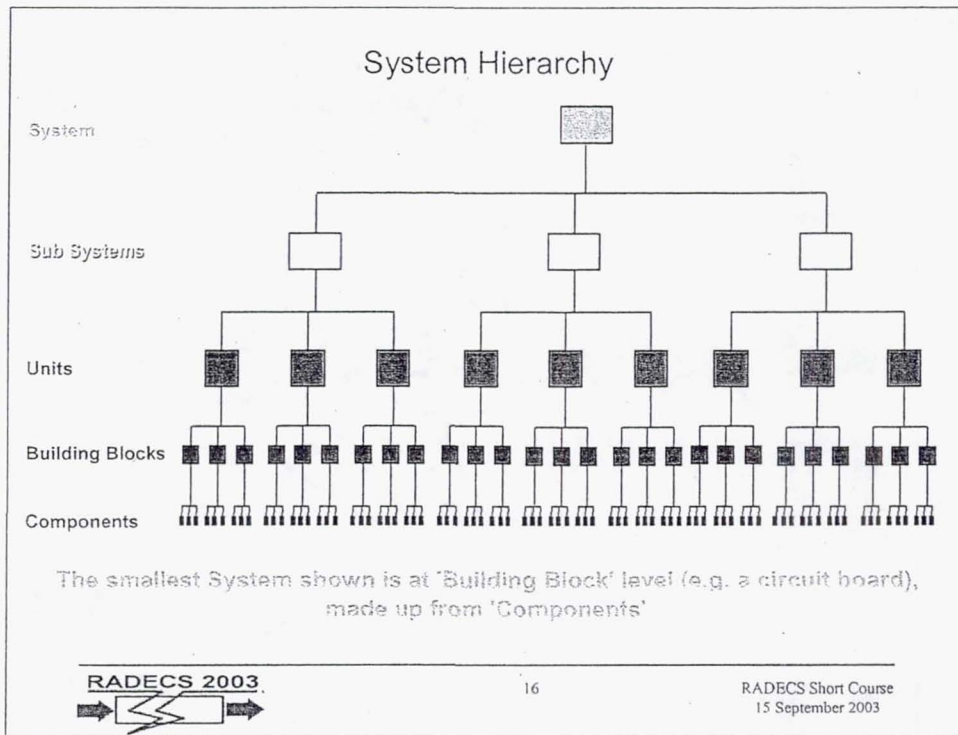
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The different roles/activities of system engineering in the project life cycle are described by the Forsberg and Mooz V chart. The V chart starts with the user needs on the upper left and ending with a user validated system on the upper right.

On the left side of the V, decomposition and definition activities resolve the system architecture, creating the details of the design.

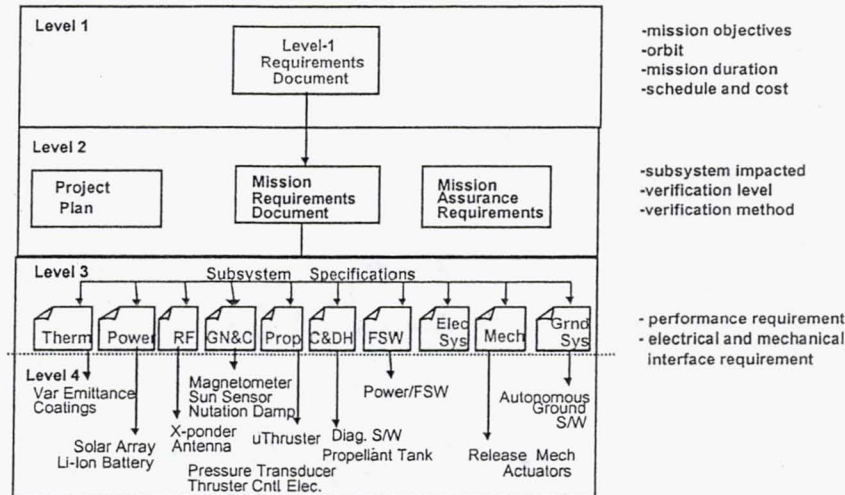
The bottom of the V is the manufacturing of the different parts.

Integration and verification flow up and to the right as successively higher levels of subsystems are verified, culminating at the system level.



A system hierarchy is defined from the higher level, the whole system, to the lower level, the building blocks made of individual components (mechanical parts, boards, electronic parts, connectors and wires,...).

Project Requirements Flow-Down



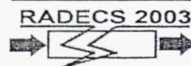
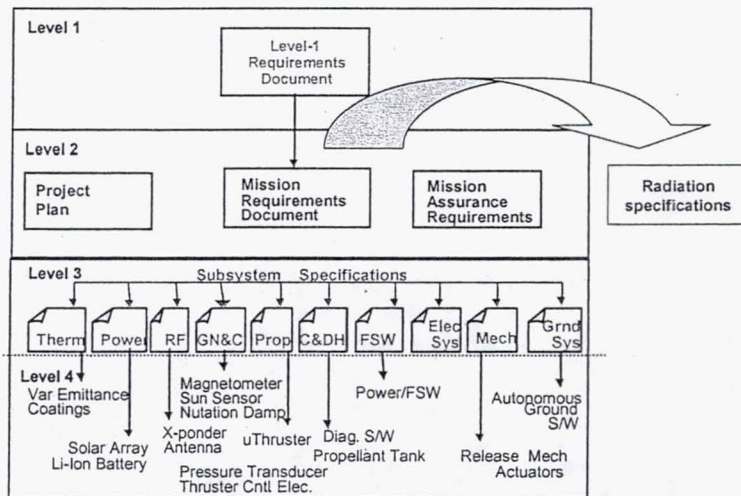
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According to the system hierarchy, this chart shows the requirement flow down in a space project:

- Level 1 requirements define the **mission objectives**, the **mission duration**, the **orbit**, and the **schedule and cost objectives** of the project. The criteria for minimal mission success are also defined.
- Level 2 requirements define the system implementation and the different subsystems to perform the mission objectives and accuracy in meeting those objectives. the **mission requirement** document gives all the requirement derived from the mission level 1 requirements. It identifies for each requirement all the subsystem impacted by this requirement and the verification level (system and subsystem) and method (test, analysis, or inspection). The requirement are categorized in different priority levels: requirements that must be achieved for minimal mission success, requirements that must be achieved, but degraded performance is acceptable, and requirement not required for minimal mission success. **Environmental Requirements** which are defined for the system to meet its transport, launch ascent and on-orbit environments (including radiation) are part of the mission requirements.
- then level 2 requirements are breakdown into **subsystem, unit, building blocks** that define the **performance requirements** and also the **electrical and mechanical interfaces** with the other subsystems.
- the bottom level are the **component level requirements** that define the component procurement specification.

Project Requirements Flow-Down



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The radiation specifications are part of the system level requirements. There are generally two radiation specifications:

- First one is the environment specification where the particle fluxes are defined, peak and average, shielded and unshielded. The environment specification also includes the dose depth curve. The type of orbit and mission duration are important factors.
- The second document is the radiation hardness assurance specification that defines the radiation level requirements, the required radiation design margin and the test requirements. Tolerable system failure rate may be defined for the SEE analysis. The spacecraft layout is an important factor for the radiation levels.
- These requirements are then reflected to the lower levels requirements: the subsystem, units, and components/parts levels:
 - At the subsystem and unit levels: specific levels for SEU tolerance levels may be derived from the system requirements; criticality levels are allocated for each subsystem. Rules for worst case analysis of TID and DD degradation may be defined. The position of the sensitive parts within a unit is an important factor. The mass and power budgets are also an important parameters.
 - At the component or piece part level, radiation requirements are part of the Part Control Plan document. Radiation test data is required for every sensitive part. Test requirements may be defined. Derating and SEE rates specifications may be defined. Radiation data acceptability criteria may be defined. The technology and part selection, the lot to lot radiation tolerance variation, the test methods are important factor at this analysis level.

Radiation requirements definition – Design Margins

- An integral part of the requirements analysis and design synthesis process.
- Allow the balancing of allocations between subsystems and subsystem elements.
- Requirements may be reduced as the design matures.
- Proper margins minimize risk and reduce the impact of requirements changes.



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Radiation requirement definition are an integral part of the system overall requirement analysis and synthesis process. For example SEE system level requirements should be expressed in view of all possible ways in which SEE could compromise mission performances concerning system availability and information quality. Each system function, telemetry and control, power and power distribution, data bus, mass memory storage, downlink, and payloads are ranked according to the degree of severity their temporary disruption or permanent loss would impose.

The top level requirements that flow out the system level requirement are allocated to every subsystem. The requirement are expressed in terms of functionality or availability, information integrity or performance, and power budget.

This allocation of functionality/availability, error allowance, performance requirement, and power budget occur early in the preliminary design, but it is a dynamic process which continues into the detailed design.

Proper design margin minimize the risks and insure flexibility without impacting too much the system cost.

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Effects Induced by the Space Radiation Environment

- Cumulative Effects
 - Induced by electrons and protons
 - Total dose effects
 - Displacement Damages
- Single Event Effects (SEE)
 - Induced by heavy ions and protons
 - Potentially destructive
 - Single Event Latchup (SEL)
 - Single Event Burnout (SEB)
 - Single Event Gate Rupture (SEGR)
 - Non destructive
 - Single Event Upset (SEU)
 - Single Event Transient (SET)
 - Single Event Functional Interrupt (SEFI)
 - Multiple Event Upset (MEU)
 - Multiple Bit Upset (MBU)
 - ...
- Other: spacecraft charging*

* outside the scope of this short course



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The mission radiation environment is a very important part of a RHA program that should be defined as earlier as possible in the program.

Once we have the external particle fluxes given by the models presented in section 1 of this short course, it is necessary to define the radiation levels within the spacecraft and to relate the environment to system degradation. This slide summarizes the different effects induced by the space radiation environment.

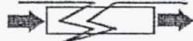
These effects are all described in detail in section 2 but the spacecraft charging. This effect needs that also need to be considered is outside the scope of this presentation.

Radiation Environment Within the Spacecraft Quantification of the Different Effects

<u>Observed Effect</u>	<u>Parameter used for quantification</u>
Total Dose Effects	Total Ionizing Dose (TID)
Displacement Damages	NIEL equivalent fluence for a selected proton energy* $F_{E0} = \sum f(E) (NIEL(E)/NIEL(E0)) \Delta E$ Displacement Damage Dose (DDD) based on Non Ionizing Energy Loss (NIEL)* $DDD = \sum f(E) NIEL(E) \Delta E$ Damage equivalent fluence for a selected electron or proton energy
Single Event Effects (SEE)	Heavy ion Linear Energy Transfer (LET) spectra and proton energy spectra

* May not be valid for III-V materials

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This slide gives the parameter that should be determined for quantification of the various radiation effects.

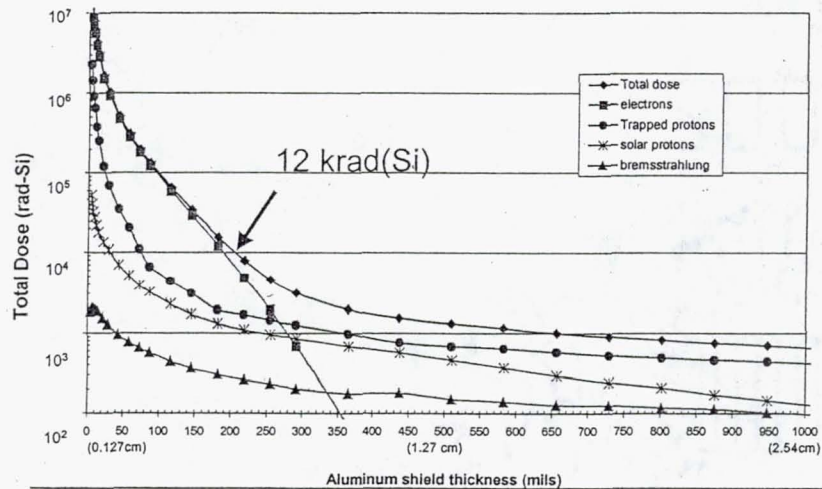
- For total dose effects, the unit of radiation is the total ionizing dose in rad(Si) or Gray. The Gray is the international unit. The rad is the unit that is commonly used in the radiation community. 1 Gray=100 rad.
- For Displacement Damage, we have three possibilities,
 - first one is the NIEL equivalent fluence for a selected proton energy,
 - or, Displacement Damage Dose based on NIEL,
 - or a damage equivalent fluence for a selected electron or proton energy.
- For heavy ion induced SEE, the unit of radiation is the LET in MeVcm²/mg, and the environment is defined by the heavy ion LET spectrum.
- For proton induced SEE, the sensitivity is related to the proton energy and the environment is defined by the proton energy spectrum.

As presented in the previous sections of this course, some of these parameters need explicit consideration of test data or models (damage equivalent fluences) or the detailed consideration of interaction geometry and mechanisms.

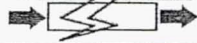
It is very important to define as accurately as possible the radiation levels within a spacecraft. Over specification leads to unnecessary costs and delays, under specification may involve very expensive retrofits or compromise the mission.

TID Top Level Requirement : Dose-Depth Curve

Total dose at the center of Solid Aluminum Sphere
ST5: 200-35790 km, 0 degree inclination, three months



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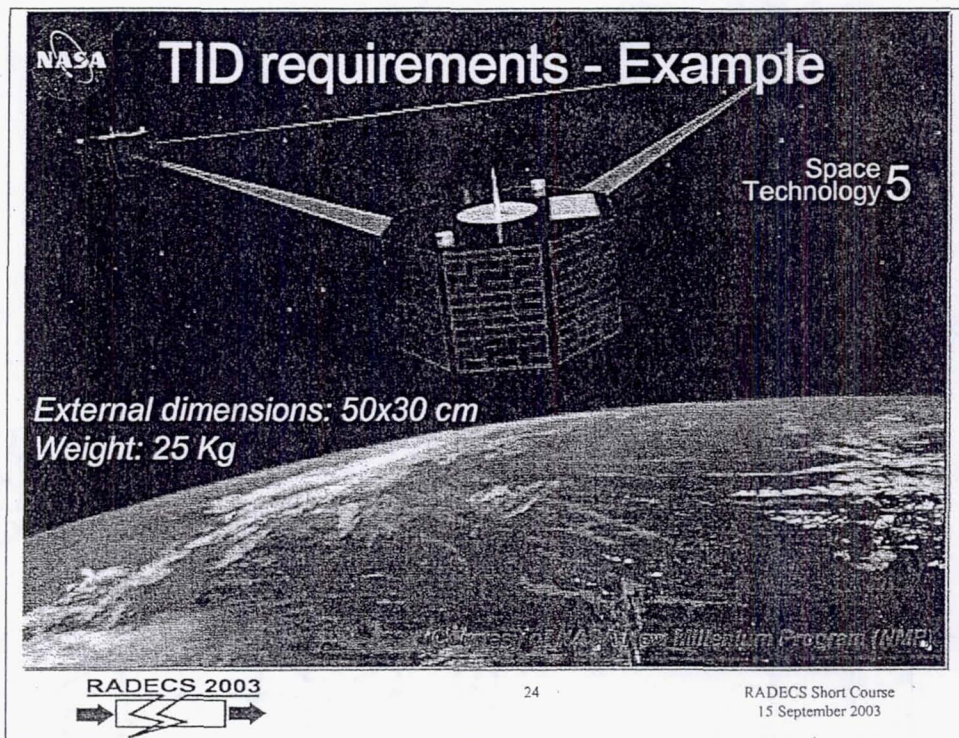


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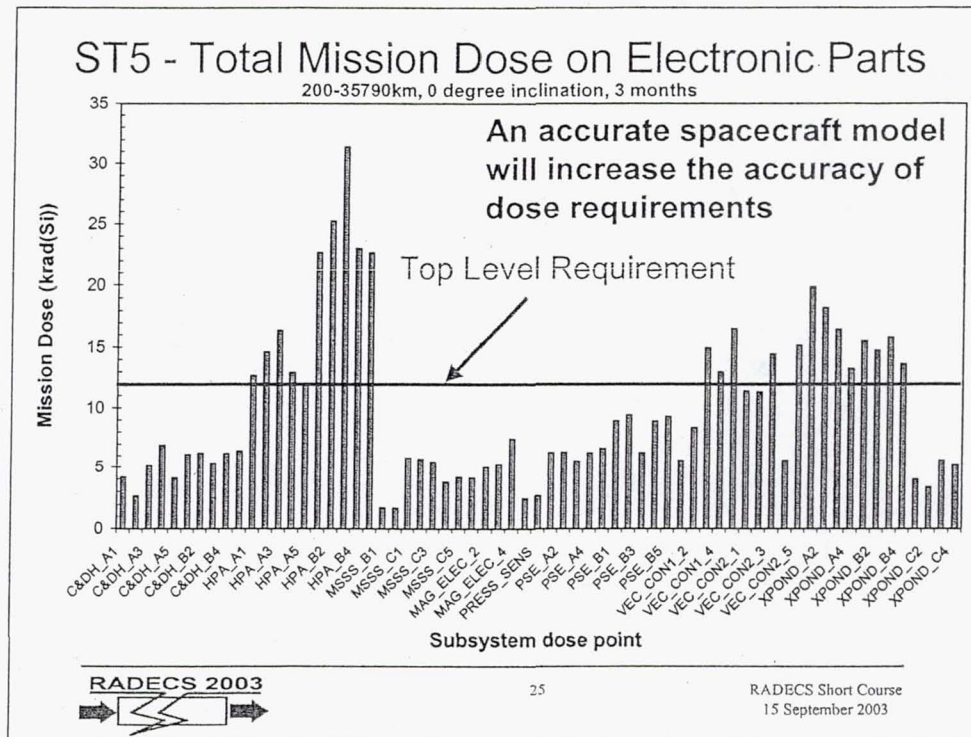
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The top level ionizing dose environment is represented by the dose depth curve. The dose depth curve generally gives the dose levels at the center of an Aluminum sphere versus the shield thickness that is the radius of the sphere.

The dose depth curve allows the definition of a top level dose requirement assuming an arbitrary shielding thickness. In the example presented in the slide, the dose level behind 200 mils of shielding is 12 krad-Si. This top level requirement may be sufficient for a low dose environment mission but generally the dose levels are too high and a more detailed analysis like the ones described in sections 1 and 2 is needed. Such analysis calculates the dose levels at a specific locations taking into account the actual spacecraft geometry and the shielding provided by all its elements.



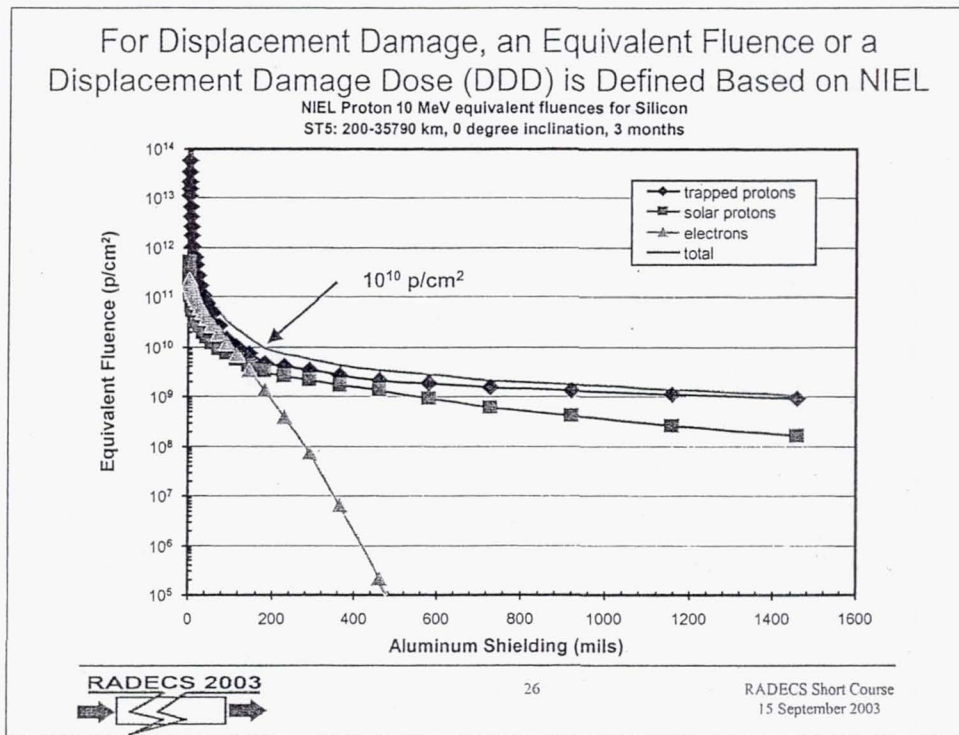
An example of a detailed radiation will be shown on the next slide. This analysis was performed for the ST5 constellation. ST5 is a technological project part of the NASA New Millenium Program. ST5 spacecrafts are nanosatellites. The external spacecraft's dimensions are 50x30cm and the total weight is 25kg.



The dose levels that were calculated by a Monte Carlo analysis on different locations within different electronic boxes.

The results presented in the slide show that even in such a small spacecraft, there is a lot of shielding and the dose levels could vary significantly from one location to another (from 2 to 32 krad). We can see that the top level requirement of 12 krad may be significantly conservative, but in some cases it is not.

This example illustrates how an accurate spacecraft model and shielding analysis can increase the accuracy of the dose requirements.



This slide shows an example of an NIEL 10 MeV proton equivalent fluence for Silicon versus shielding thickness of a solid sphere geometry to define the displacement damage environment.

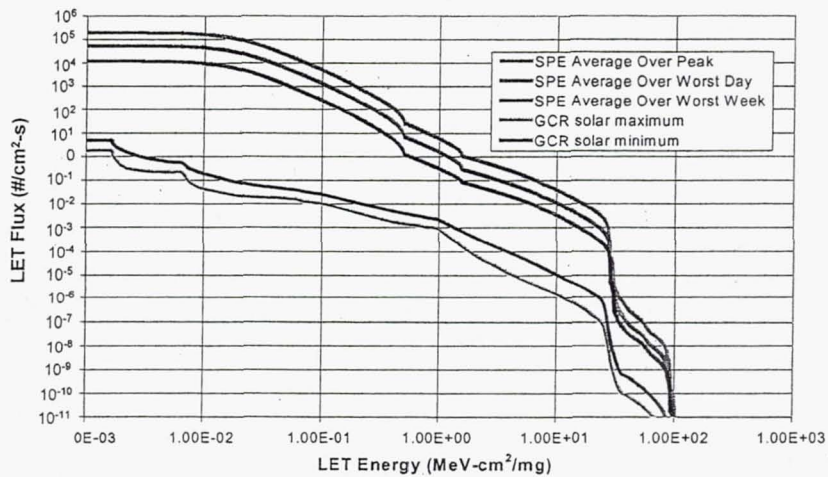
NIEL values have been calculated for Si, and different III-V materials. Cheril Marshall presents in her 1999 short course presents the limitations of the NIEL concept. Generally the NIEL gives a good estimation of the degradation for Silicon, but does not agree with actual energy dependence of degradation for III-V materials (for more details see sections 2 and 3 of this course).

For a top level requirement, an arbitrary value of shielding is considered. In the example shown in the slide, behind 200 mils of shielding the mission equivalent 10 MeV proton fluence for Silicon devices is 10^{10} p/cm². With this fluence level, the DD on linear bipolar devices will not be a concern for this mission.

Like for total dose when the top level requirement is too high for a specific device, the shielded particle spectra at a specific spacecraft location can be calculated with a Monte Carlo code. Then, the equivalent fluence can be calculated.

Heavy Ion Environment is Defined for a Conservative Value of Shielding

Integral LET Spectra at 1 AU (Z=1-92) for Interplanetary orbit
100 mils Aluminum Shielding, CREME96



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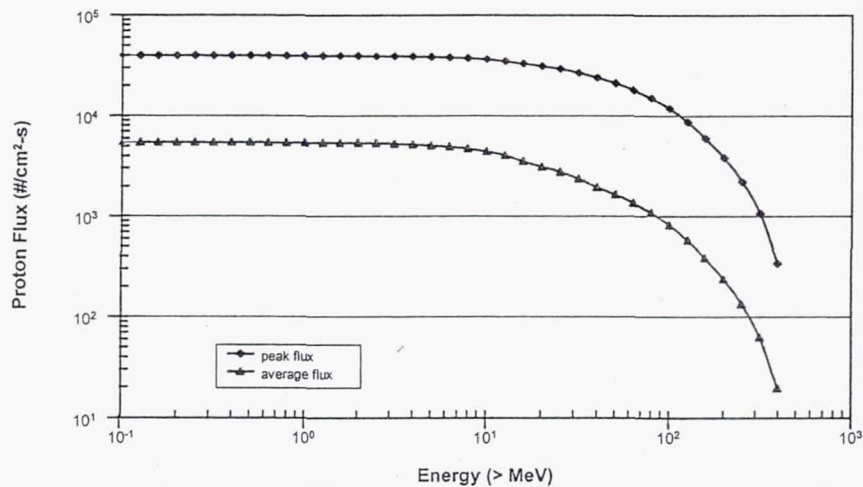
For SEE studies, the contribution of the different heavy ion spectra is combined to define the Integral LET spectra. These spectra are calculated for a conservative value of shielding (ie 100 mils). An accurate shielding analysis is generally not necessary because the GCR spectra will not change significantly for higher shielding thickness. However, an accurate shielding analysis is needed to get an accurate estimation of the SPE environments. These calculation are performed with the CREME96 code.

The figure shows an example of the particle fluxes versus LET of GCR for an interplanetary orbit during solar maximum and solar minimum activity.

The figure also shows the different SPE LET spectra models, that are available in CREME96: the worst week, the worst day and the 5'peak of the solar event.

The Proton SEE Environment is Defined for a Conservative Value of Shielding. Orbit Average and Maximum Fluxes are Defined

Trapped Proton Integral Fluxes, behind 100 mils of Aluminum shielding
ST5: 200-35790 km 0 degree inclination, Solar maximum



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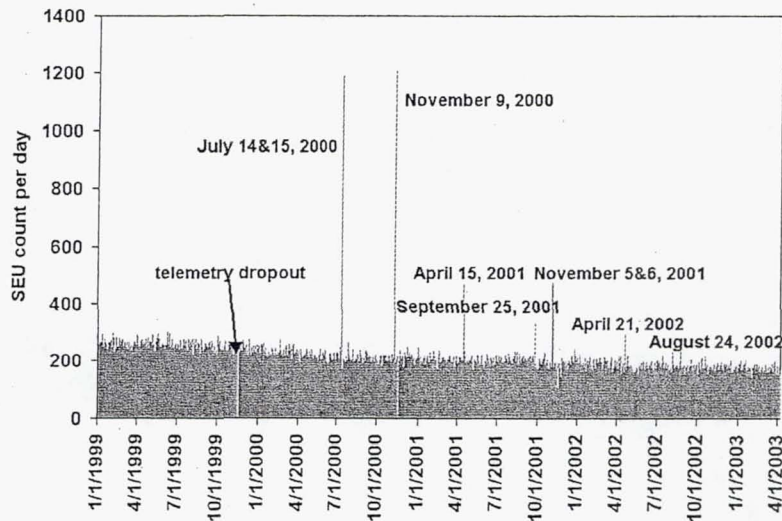
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The proton SEE environment is the proton flux spectrum calculated behind a conservative Aluminum shielding value (ie 100 mils). This slide shows an example of orbit average and peak trapped proton fluxes behind 100 mils of shielding.

We can see in this example a significant difference between the orbit average fluxes and the peak fluxes. The electronics can be perturbed by these peak fluxes; therefore, it is important to define these peak fluxes.

In addition to the trapped proton environment, the solar proton environment needs to be considered.

SEE environment – SPE example



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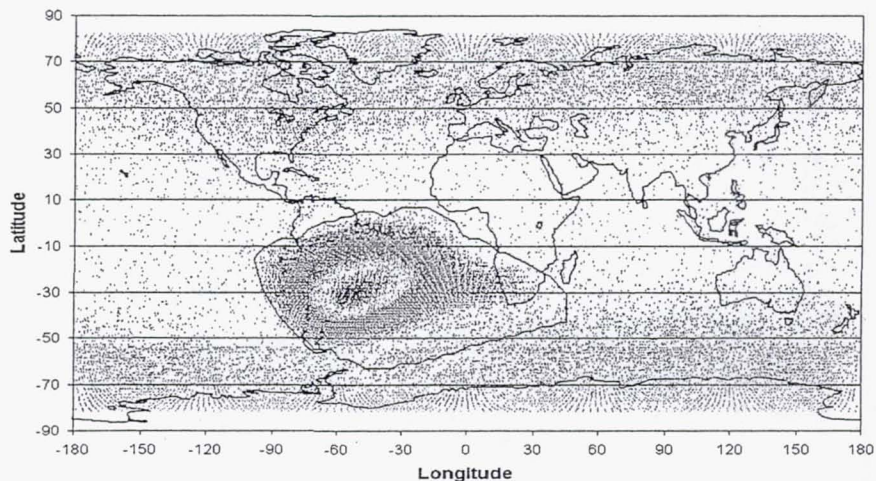
This slide shows the daily numbers of SEU observed in the Orbview-2 spacecraft Solid State Recorders (SSR) during a 4-year period.

We can see extremely high numbers of SEUs during Solar Particle Events(SPE). This shows that it is important to consider not only the background environment but also the SPE environment in the SEE analysis.

We can also see the effect of solar activity on the SEU numbers due to the background environment. The number of SEU per day decreases with the increasing solar activity. In the beginning of January 1999, the average SEU count was 255; during the first months of 2003, the average SEU count per day was about 170.

SEE environment – peak fluxes example

• 1 SEU • $1 < \text{SEU} < 10$ • $10 \leq \text{SEU} < 20$ • $20 \leq \text{SEU} < 40$ • ≥ 40 SEU



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This slide shows the geographical distribution of the SEU accumulated during four years in the Orbview-2 SSRs. About 80% of the SEUs occur within the South Atlantic Anomaly (SAA) where the spacecraft spends less 20% of its orbit time. This results in very high SEU rates in this region.

This example shows the importance to consider not only the daily average fluxes but also the peak fluxes in the SEE analysis.

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 - TID/DD
 - SEE
- Conclusion



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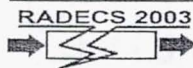
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The hardness of any electronic system depends on the hardness of every individual component (mechanical parts, boards, electronic parts, connectors, wires,...).

Because of their sensitivity to radiation, the major emphasis of a hardness assurance program is on electronic parts and on the materials outside the spacecraft that receive the highest radiation levels.

Parts and Material Potential Sensitivities in the Space Environment

- | | |
|---|---|
| <ul style="list-style-type: none"> • <u>Materials</u> | <ul style="list-style-type: none"> • Total Dose Effects • Displacement Damages |
| <ul style="list-style-type: none"> • <u>CMOS electronic parts</u> | <ul style="list-style-type: none"> • Total Dose Effects • SEE |
| <ul style="list-style-type: none"> • <u>Bipolar electronic parts</u> | <ul style="list-style-type: none"> • Total Dose Effects • Displacement Damages • SEE |
| <ul style="list-style-type: none"> • <u>Optoelectronic parts</u> | <ul style="list-style-type: none"> • Displacement Damages • Total Dose Effects • SEE |
| <ul style="list-style-type: none"> • <u>Solar cells</u> | <ul style="list-style-type: none"> • Displacement Damages • Total Dose Effects (cover glass) |



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Materials are sensitive to total dose effects and displacement damages that change their mechanical and electrical characteristics. But generally these degradations appear at high levels of irradiation (tens of Mrad, 10^{15} p/cm²). So, they are not a concern when they are used inside a spacecraft. But, outside the spacecraft where there is a significant amount of radiation, the radiation sensitivity of material needs to be looked for. This includes the insulating material on the cables and wires used outside the spacecraft. For example, Teflon loses its insulating characteristics after about 1 Mrad, and generally coaxial cables using Teflon cannot be used. Other concerns are all the materials used in optical or optoelectrical systems: coverglass coating of solar cells, optical fibers, lenses,....

CMOS devices are sensitive to total dose effects and all types of SEE effects. SEL is one of the main concerns.

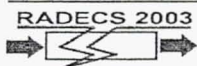
Bipolar electronic parts are sensitive to total dose effects and displacement damage. But in most missions, the displacement damage degradations are negligible. Bipolar electronic parts are also sensitive to SEE. For example bipolar linear devices are extremely sensitive to SET.

Optoelectronic parts are extremely sensitive to displacement damage. They are also sensitive to total dose effects. The SEE sensitivity is high, and for some parts proton can induce SEE by direct ionization. This leads to huge event rates on orbit.

Solar cells used on the solar panels are exposed to high levels of radiation. They are mainly sensitive to Displacement damage but also total dose that degrades the optical characteristics of the coverglass coating as mentioned before.

Part Selection

- Selection criteria:
 - Performances
 - Reliability
 - Radiation tolerance
 - Cost
 - Availability
 -
- The market's options:
 - High reliability parts
 - Radiation Hardened parts
 - Radiation Tolerant parts
 - Non Hardened parts
 - COTS



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There are a lot of criteria besides radiation hardness involved in electronic part selection.

For some functions Radiation Hardened (RH) devices, and Radiation Tolerant (RT) devices are available. RH devices have been designed and built for radiation hardness. RT devices may be either parts built and/or designed for improved radiation tolerance, or standard parts on which the manufacturer provides part hardness assurance verification testing. RH or RT parts are generally more expensive than the non hardened parts; however, their possession cost may be lower. RH or RT parts may still be sensitive to the space radiation environment. For example, a TID hardened part may still be sensitive to SEE. A TID tolerant part for high dose rate applications may show an Enhanced Low Dose Rate Sensitivity (ELDRS).

Some manufacturers propose non hardened devices packages in multilayer Radiation Hard packages. These packages provide a very effective shielding in electron rich environments. However, the information provided by the manufacturer can be misleading, and the shielding provided by the package should be assessed for each particular environment.

Non hardened high reliability parts have generally an history of use in space projects and radiation data on these parts can be found. But for the most advanced parts, for example high density memories or high performance ADC, that often are the key elements for a given electronic function, there are only available as COTS parts and often no valid radiation data is available. For these parts, a careful selection and evaluation is needed as soon as possible in the program development.

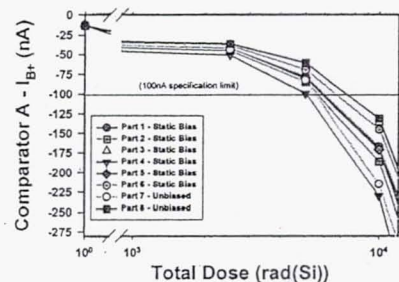
Example : Voltage comparator

Part type	Manufacturer	TID tolerance	SEE tolerance
IS139ASRH	Intersil	300 krad	SET > 84 MeVcm ² /mg (TMR)
HS139RH		300 krad	SET LETth = 20 MeVcm ² /mg
LM139AJLQMLV	NSC	50 krad	Sensitive to SET
LM139		~ 5 krad	Sensitive to SET
139	Maxwell	> 100 krad depending upon orbit and space mission	SET > 59.8 MeVcm ² /mg

NSC 50 krad radiation tolerant

Parameter	Pre irradiation limit	Post irradiation limit
Vio	+/- 2 mV	+/- 2.5 mV
Iib	100 nA	110 nA
trLH	0.8 ns	0.9 ns

NSC low dose rate test data



After NAVSEA/CRANE test report, 2002



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This slide shows the different options that are available in term of hardness tolerance for the selection of a 139 voltage comparator. The highest level of hardening is offered with the IS-139ASRH. The part is guaranteed for a 300 krad dose level. However, this part may be sensitive to an Enhanced Low Dose Rate Sensitivity (ELDRS), and the actual part's tolerance in the space environment will be lower. The device is SET free because of a Triple Module Redundancy (TMR) design.

The HS139RH is also guaranteed for a 300 krad dose level, and there is a concern about ELDRS as well. The manufacturer gives a SET LET threshold of 20 MeVcm²/mg. This is quite ambiguous, because for low input differential input voltages, this part is known to have a lower LET threshold.

National Semiconductor proposes a 50 krad radiation tolerant LM139. This part is exactly the same than the non tolerant LM139. The part demonstrates a tolerance at high dose rate; however, this part is known to show ELDRS. Low dose rate testing shows a 5 krad tolerance. LM139 from NSC is also very sensitive to SET.

Maxwell proposes a 139 voltage comparator packaged in a radiation hardened package. Maxwell states that the package provides a greater than 100 krad radiation dose tolerance in a geostationary orbit. This definition is very ambiguous. It does not give any idea of the radiation margin and does not provide any information for other radiation environments. The radiation hardened packages are known to be very efficient for electron dominated environment like the geostationary orbit, but they are less efficient in proton dominated orbits.

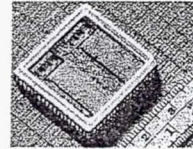
Reference:

•R. Koga, S.H. Crain, K.B. Crawford, S.C. Moss, S.D. Lalumondiere, J.W. Howard, "Single Event Transient (SET) Sensitivity of Radiation Hardened and COTS Voltage Comparators," IEEE NSREV 2000 data workshop proceedings, 2000.

Sources of Radiation Data

- In house data for previous projects
- Available databases:
 - NASA-GSFC: <http://radhome.gsfc.nasa.gov>
 - NASA-JPL: <http://radnet.jpl.nasa.gov>
 - ESA: <http://escies.org>
 - DTRA ERRIC: <http://erric.dasiac.com>
 - NRL REDEX: <http://redex.nrl.navy.mil>
- Other sources of radiation data:
 - IEEE NSREC data workshop, IEEE Trans. On Nuc. Sci., RADECS proceedings,..
 - Vendors ?

Stacked devices and hybrids
can present a unique challenge
for review and test

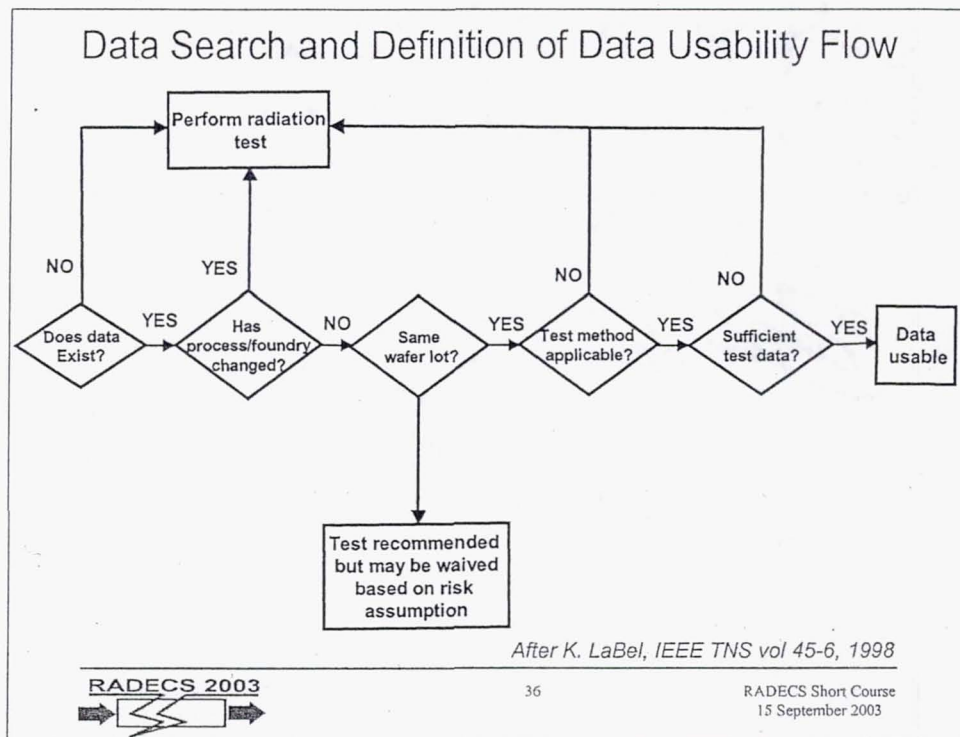


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When the radiation tolerance of a part is not known, a radiation test shall be performed.

Radiation testing is expensive and should be avoided when possible. A careful data search and analysis can circumvent unnecessary tests. The main sources of radiation data are presented in this slide.



This slide shows the flow of definition of data usability. If the data satisfies all these criteria, it can be used for the project. If one of these criteria is not satisfied, data should be taken.

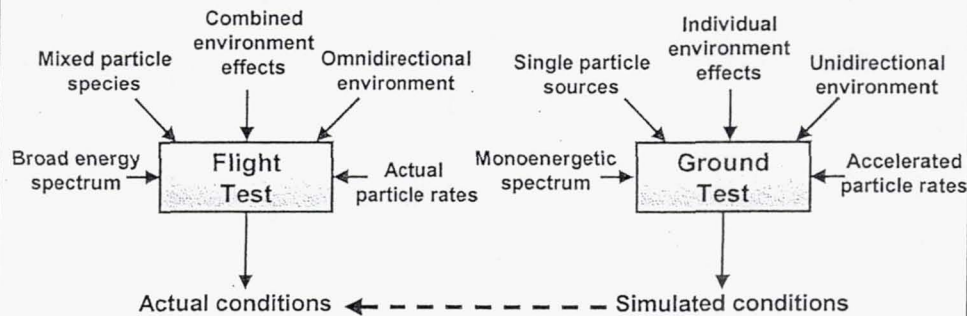
The first criteria is that the data should have been taken on a part representative of the flight lot: same design, same process, and same foundry. It is preferable to get data from the same wafer lot as well. This may be waived on parts where the part process information is known and the radiation tolerance is well above the requirements. For COTS, these criteria are very rarely satisfied and each procurement lot needs to be tested.

There are a lot of issues related to the simulation of the actual space environment with radiation sources. To deal with these requirements test standards were developed. The test data should have been taken according to these test standards (see following slides).

The operating mode, bias, and temperature have a significant effect on the radiation test results, as well. It is important to compare the test conditions to the device usage in the application.

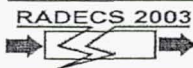
The data collected may also not be sufficient. An important parameter for the application may not have been measured. This assessment often implies the understanding of the designer's sensitive parameters

Radiation Test Issues - Fidelity



*How accurate is the
ground test in predicting Space Performance?
Example, how does dose degradation and aging effects affect SEE performance?*

After E. Stassinopoulos and K. LaBel



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This slide compares the irradiation conditions in the laboratory with the actual conditions in space. All these differences are source of significant uncertainties in the fidelity of the simulation of the space radiation environment in the laboratory.

Radiation test standards and guidelines

- **TID**

- US MIL-STD 1019.6 **New**
- ASTM F1892-98
- ESA/SCC 22900

- **SEE**

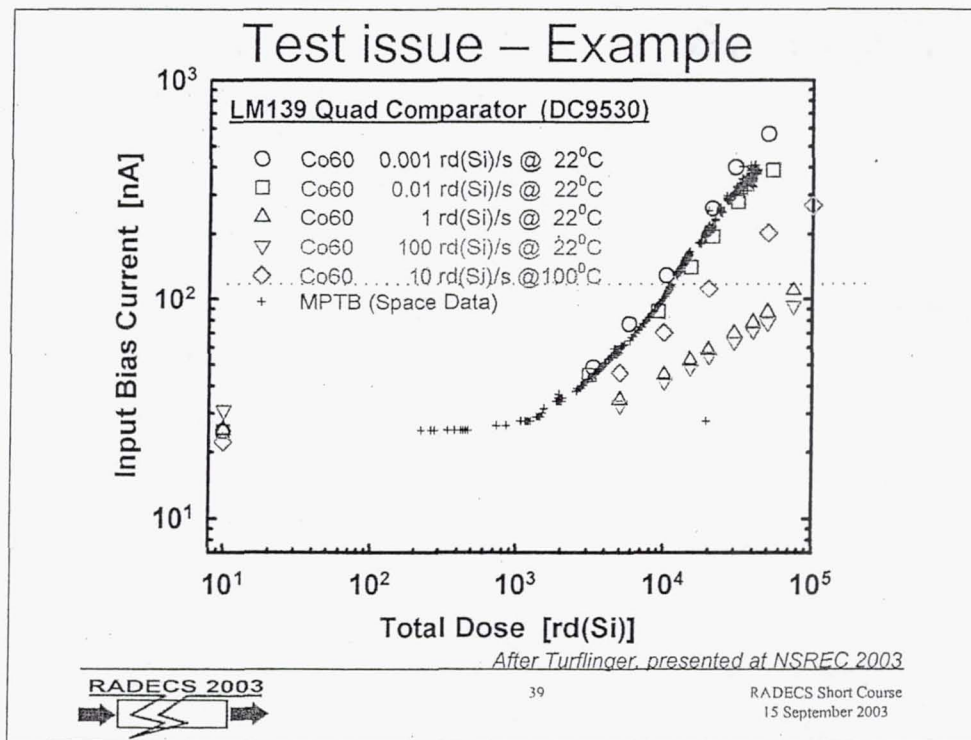
- JEDEC/EIA JESD13.4
- ASTM F1192-90
- ESA/SCC 25100



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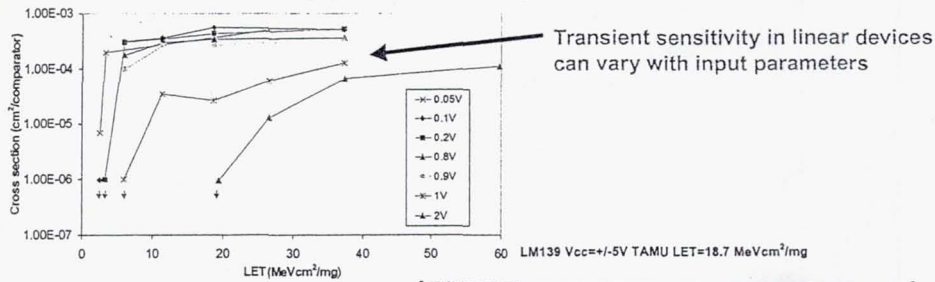
In order to ensure the best possible test fidelity, it is important to perform the radiation test in compliance with the existing test standards.



This figure compares the degradation of input bias current versus dose of a LM139 voltage comparator for different dose rates with actual in flight degradation observed on MPTB. We can see in the figure that the actual in-flight degradation is comparable to the one with the low dose rate irradiation. High dose rate data do not bound the actual space degradation. This is often the case for the high dose rate test data taken on linear bipolar devices that show Enhanced low Dose Rate Sensitivity (ELDRS).

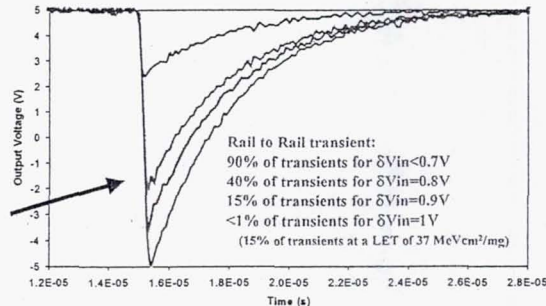
Accelerated testing methods or use of higher design margins as suggested in the test method MIL1019.6 may be an alternative to the low dose rate testing for these devices.

Data Applicability - Example



LM139 NSC

Transients in a linear device
can vary with input parameters



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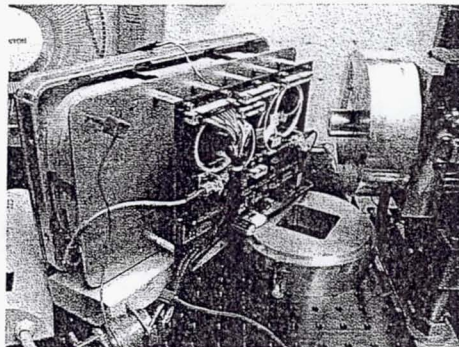
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The failure mechanisms of many devices exposed to radiation are a strong function of the operating mode, bias and temperature. Therefore, Radiation test data is often application specific. Power supply voltage, operating frequency, circuit load, test pattern, temperature, and bias configuration have an effect on test results.

For example, this slide shows the LM139 voltage comparator from National Semiconductor Single Event Transient (SET) cross section curve (top left figure) and SET characteristics (bottom right figure). We can see the significant effect of the input bias conditions. For low differential input voltages, not only the SET sensitivity is higher but also more transients have a large amplitude.

Radiation Test Requirements

- Determine the types of tests that are needed
 - Mission-specific issues
- Define appropriate test levels
 - Sample size, particle, irradiation levels
- Testing should mimic or bound the flight usage, if possible
 - *Worst-case issues should be included*



A fiber optic link awaiting protons for SEE tests at UCDavis

Once the part list is reviewed versus archival data, the devices that need testing are identified. The types of tests depend on the type of device and the mission. For example in a geostationary environment DD testing is not necessary for most parts but solar cells and sensors.

The irradiation levels may also vary in function of the mission. However, it is always a good policy to test the devices up to the highest radiation levels. Then the test data may be used for other missions with higher radiation levels. The sample size is also a function of the number of devices that will be used in the application (see the example in the next slide).

As mentioned before, the simulation of the operating conditions of the device is another important factor. Test conditions should apply to the specific circuit application.

Sample size - example

- HST SSR 15 Gbit (1440 16Mbit DRAM)
 - Preflight test
 - Heavy ion and proton induced SEU
 - Heavy ion induced SEFI but no proton induced SEFI (test on 3 parts with 10^{10} p/cm² fluence) -> negligible risk (~1/200 years)
 - In flight: Observation of proton induced SEFI (2 in 9 months)
 - Investigation test on 100 parts with 1.5^{11} p/cm² fluence
 - 9 Proton induced SEFI observed (Cross section ~ 10^{-13} cm²/die)
 - Predicted rates comparable to the flight rate

After K. LaBel IEEE TNS vol45-6, 1998



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The Hubble Space Telescope (HST) is flying a 12 Gbit Solid State Recorder (SSR) containing 1440 16 Mbit DRAM. This SSR experienced anomalous events (large number of errors, about 100, correctable by the Reed Solomon EDAC but that cannot be cleared by writing new data to the erroneous locations. These errors are due to an error in the redundancy latch in these dice).

These SEFI were observed during heavy ion pre flight testing but not during proton testing. Predicted heavy ion induced SEFI rates were very small (< 1per 200 years).

After the first nine months of flight, two anomalous events were observed. An investigation was initiated to find the cause of these in-flight anomalies. One issue to resolve was the question of proton induced SEFI on the DRAMs. Therefore, it was decided to perform further proton testing. Based on the observed rate, the expected cross section was about 10^{-13} cm²/device.

100 devices were irradiated up to a fluence of $1.5 \cdot 10^{11}$ p/cm² corresponding to a deposited dose of 20 krad for a 63 MeV proton energy. A total of 9 events were observed that had similar characteristics to the in-flight HST anomaly. The measured cross section is $5 \cdot 10^{-13}$ cm²/bit, and the calculated in-flight rate of SEFI is 2.2 per year. This is the same order of magnitude as the observed in-flight rate of two in nine months.

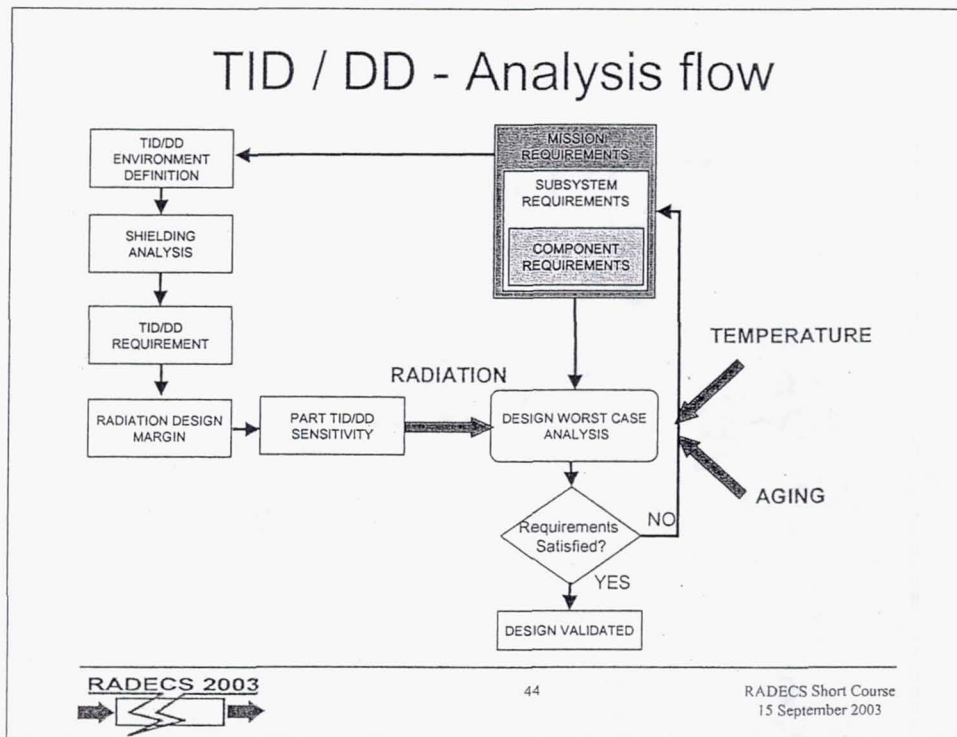
RHA Outline

- Introduction
- Programmatic aspects of RHA
- RHA components
 - requirements and specifications
 - mission radiation environment
 - parts selection and radiation tolerance
- Analysis at the function/subsystem/system level
 - TID/DD
 - SEE
- Conclusion



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There are different ways to analyze the TID and DD response of a system. This flow chart shows the way we do it at NASA.

A **radiation design margin** is applied to the requirement to define the **design dose or equivalent fluence**, and the test data is used to define the part degradation at this design dose or equivalent fluence level. The degradation obtained is used as the radiation input to the design worst case analysis.

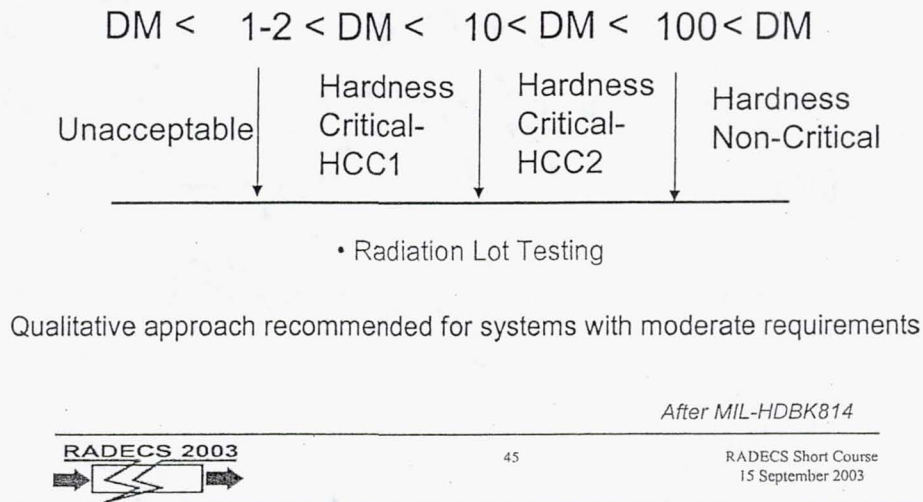
The design Worst Case Analysis combines the effects of radiation, temperature and parts aging. This analysis is performed in each engineering subsystem and science instrument to demonstrate that the design will work in its environment according to the requirements. The failure definition is then determined by the system application:

- Functional: the circuit no longer performs required operation
- Parametric:
 - Digital- e.g. standby power, switching times
 - Linear- e.g. gain, offset voltage, reference voltage, operating frequency
 - Mixed signal- e.g. resolution, accuracy, operating frequency, distortion, missing codes

If the requirements are satisfied, the design is validated. If the requirements are not satisfied, there are three alternatives: replacement of the part by a less sensitive one, mitigation, or a relaxation of the performance requirements.

Generally for a given part, either TID effects or DD are dominant. Therefore only one effect is considered for a given part. But in some cases, both effects have to be combined. This is for example the case for the analysis of the degradation of optocouplers (see NASA guidelines for optocouplers referenced at the end of the presentation).

Design Margin Breakpoint (DMBP)



This slide shows the DMBP part categorization method to determine the acceptability of the parts as defined in MIL HDBK814 TID and DD radiation hardness assurance procedure. DMBP is a qualitative approach that is recommended for systems with moderate requirements.

A design margin less than 1 to 2 is considered as a high risk and is not acceptable.

A design margin between 1-2 and 10-100 is considered as a medium risk. Radiation Lot Testing is recommended.

A design margin higher than 10-100 is considered as a low risk, and no further action is recommended.

At NASA, the approach is based on risk assessment. The standard design margin is 2, and higher design margin are applied or radiation lot testing are performed on a case by case basis.

For example, for DD on optocouplers, when the test has only been performed for one proton energy, a design margin of 10 is recommended.

Another example is the case of commercial parts commercial parts. they are considered a high risk. For these parts radiation lot testing is performed on all procurement lots.

Part Categorization Criteria (PCC)

Log normal distribution law

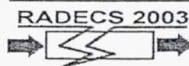
$$PCC = \exp(K_{TL}s)$$

K_{TL} = One sided tolerance factor based on sample size n ,
confidence level C and probability of survival P_s
 s = standard deviation of sample data

$$DM < 1-2 < DM < PCC < DM$$



After MIL HDBK-814



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A statistical analysis of the test data gives a more quantitative estimation of the risk. The PCC method (or the one sided tolerance limit) defined in the MIL-HDBK 814, is a statistical analysis based on the average and the standard deviation of the test data. It is generally considered that radiation degradation distribution follow a log-normal distribution law. For a log normal law, the part categorization criteria PCC is defined as

$\exp(K_{TL}s)$, where:

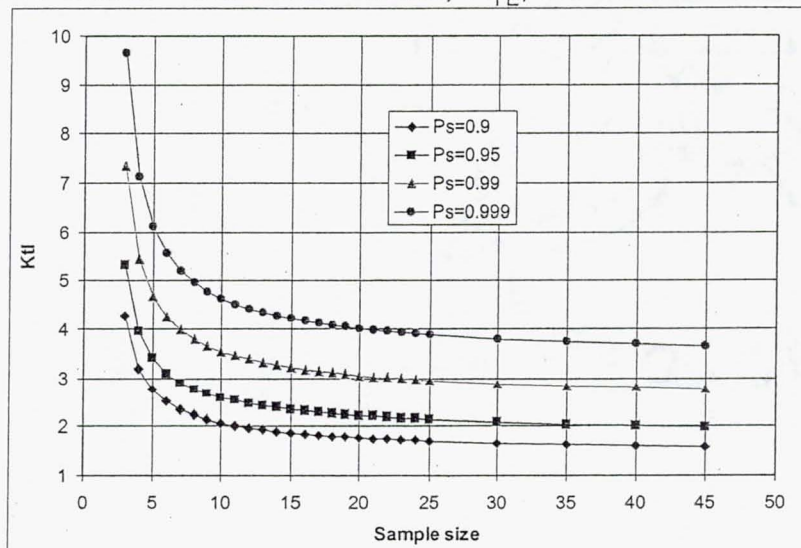
- K_{TL} is the one sided tolerance factor based on sample size n of test data, confidence level C and probability of survival P_s
- s is the standard deviation of the sample data

To apply the PCC method, one may define a probability of survival with a confidence level.

The categorization criteria are:

- A design margin less than 1 to 2 is considered as a high risk
- A design margin between 1-2 and PCC is considered as a medium risk and radiation lot testing is recommended.
- A design margin $>PCC$ is a low risk, because there only a very small probability that one part exceeds the one sided tolerance limit.

One-Sided Tolerance Limits, K_{TL} , for 90% Confidence



After R Pease, Rad Phys Chem 43, 1994



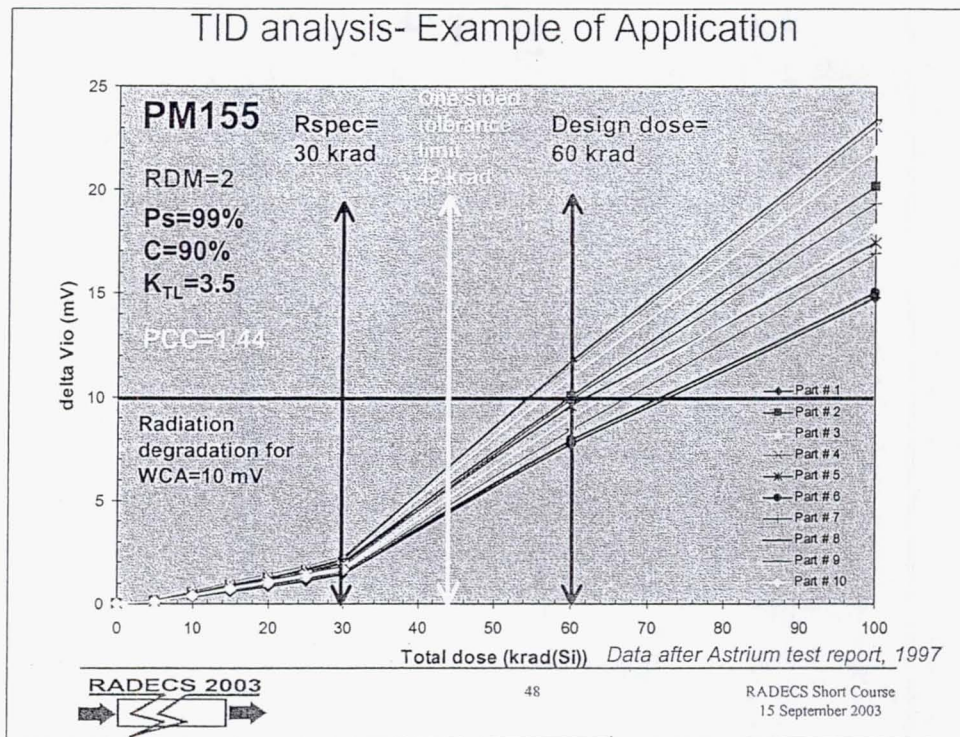
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This figure gives K_{tl} value in function of sample size for different values of P_s at a 90% confidence level.

The values of K_{TL} for different P_s and C are given in MIL HDBK-814 hardness assurance procedure.

We can see that below a sample size of 5, K_{tl} increases very quickly. This means that below this number the sample size is no longer statistically significant.



This slide shows an example of TID analysis for a PM155 operational amplifier. 10 parts were tested. The offset voltage is one of the most sensitive parameter and it is also the most critical for the application.

- The specification level is 30 krad.
- The radiation design margin is 2,
- The Design Dose is 60 krad.
- For 60 krad, the radiation degradation to consider for the WCA is 10 mV. With value the WCA demonstrated that the function will meet its performance requirements.

We can calculate the PCC to estimate the risk.

- If we consider a P_s of 99% and a confidence level of 90%, with $n=10$, $K_{tl}=3.5$
- and $PCC=1.44$

In this example $R_{DM} > PCC$,

- the risk is low that the part exceeds the 10 mV degradation at a dose below 42 krad.

This part can be used in this application without any further action.

TID mitigation

- Reduce the dose levels
 - Improve the accuracy of the dose level calculation
 - Change the electronic board, electronic box layout
 - Add shielding
 - Box shielding
 - Spot shielding
- Increase the failure level
 - Test in the application conditions
 - Test at low dose rate (CMOS only)
 - Tolerant designs (cold redundancies,...)
- Relax the functional requirements



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When the requirements are not satisfied for a given part, the change to a less sensitive part is always a risky choice. This kind of trade-off occurs generally late in the project development phase. If there is no equivalent part available, the changes in the electronic box design may be significant. In addition there is often no guarantee whatsoever that the new selected part will have a better tolerance.

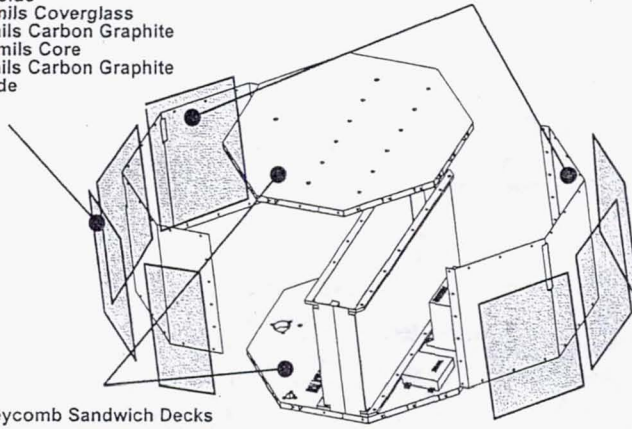
One of the best options, as developed in the following slides, is to improve the accuracy of the dose level calculation. If this is not sufficient, add-on shielding may be possible without causing too many changes in the electronic box design. Spot shielding may reduce significantly the dose level received by one part without impacting the box weight budget.

The failure levels are generally defined based on ground test data taken for worst case bias, irradiation, and temperature conditions. A test in the actual application bias condition will result in higher failure levels. For example CMOS parts degrade less when they are unbiased. Designers may take advantage of this characteristic of CMOS parts, when the part is not always ON in the application. Cold redundancy designs may be used as well. In addition, for CMOS parts when the interface state degradation is negligible, a low dose rate test will give higher failure levels.

The functional requirements used in the design worst case analysis may also be relaxed.

TID/DD mitigation – Shielding Spacecraft structure

- Honeycomb Solar Array Panels
 - 8 Panels
 - ~0.175mils
 - Outside
 - 30 mils Coverglass
 - 10mils Carbon Graphite
 - 125mils Core
 - 10mils Carbon Graphite
 - Inside
- Sheet Metal Side Wall serves as closeout
 - 32mils Sheet Al 6061
- Honeycomb Sandwich Decks
 - 1/2" core (Composite), 0.015" Facesheets (Al)
 - Equivalent ~30mils Al



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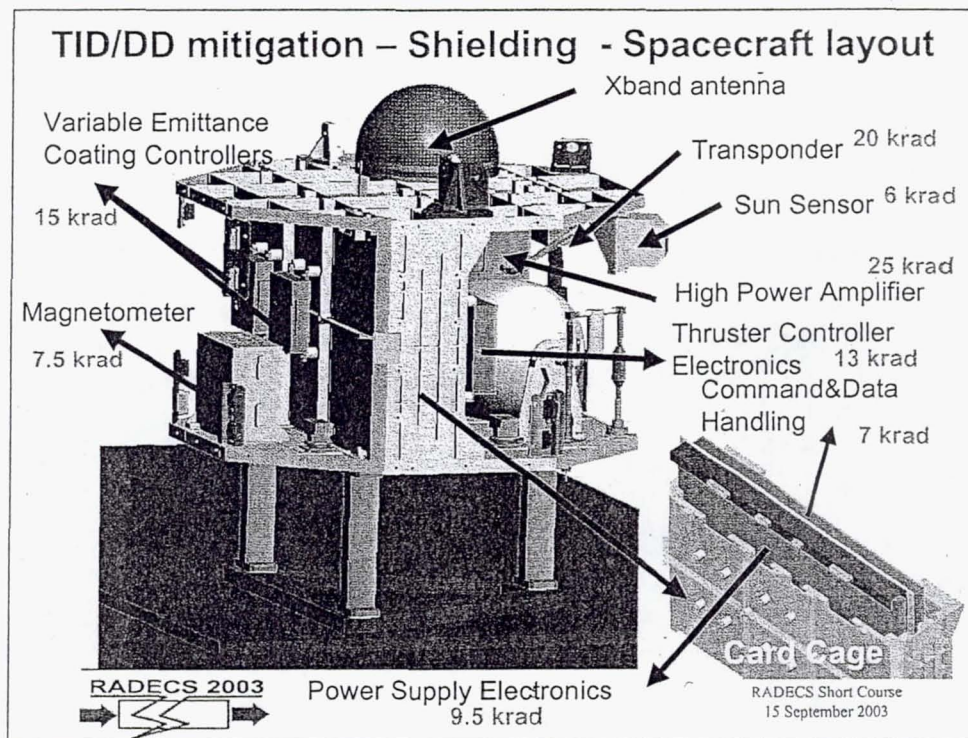
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Because of the ease of stopping some parts of space radiation, all components of a spacecraft can be thought of as shielding one another. All mass surrounding a spacecraft component can be regarded as shielding one another, even though that mass serves some other primary, usually structural, purpose.

For example, this slide shows a drawing of the ST5 spacecraft structure. For this spinning satellite structure the solar arrays wrapped around the spacecraft's perimeter provide about 100 mils of Aluminum shielding. In addition the sidewalls provide 32 mils of Aluminum shielding. The top and bottom decks provides an equivalent of 30 mils of Aluminum shielding.

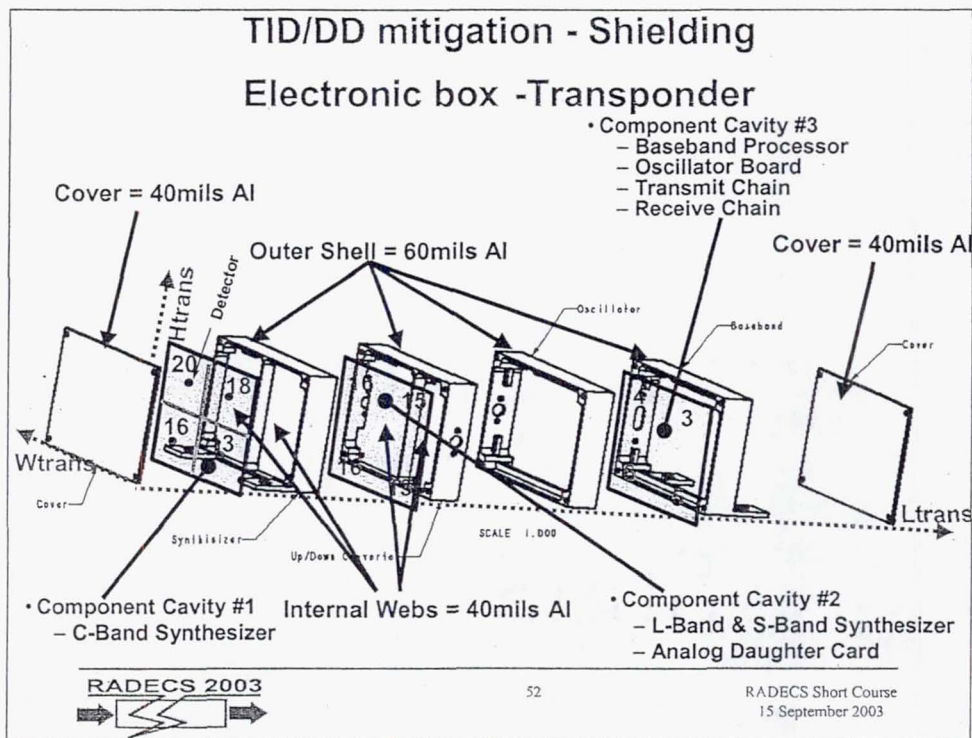
The ultimate aim of the spacecraft design practice is to use "built-in" shielding such as the need for "add-on" shielding is minimized. Spacecraft layout has a fundamental importance in the design of a radiation-tolerant spacecraft.



The layout of the amount of mass in the spacecraft has a strong influence on the radiation dose reaching the sensitive electronic parts. Not only the spacecraft structure, but the electronic box provide shielding.

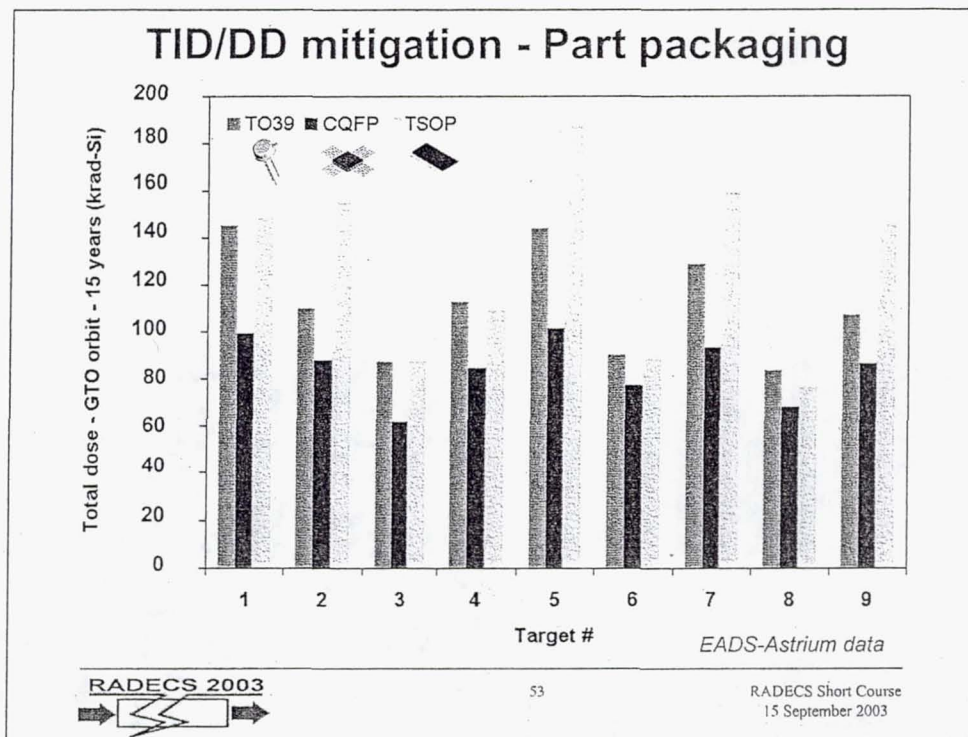
This slide shows the layout of the ST5 spacecraft with the main components and the maximum dose received in these box. The electronic box in the center of the spacecraft, like the power supply electronics and the command and data handling, receive less dose than the box near the edge of the spacecraft.

However, the closer the shielding mass is, the most efficient it is. Shielding provided by electronic box cover, and circuit boards provide a significant amount of shielding. This is for example the case for the ST5 sun sensor. The maximum dose level inside the Sun sensor is only 6 krad even though this box is located outside the spacecraft.



Electronic box cover, and circuit boards provide a significant amount of shielding. For example, an integrated circuit in the center of a stack of printed circuits boards may be exposed to only one tenth of the dose received by the same circuit on the uppermost board of a stack.

This slide shows the drawing of the ST5 transponder. We can see that the dose received in the board number 3 is about 4 times less than the dose received on board number 1.



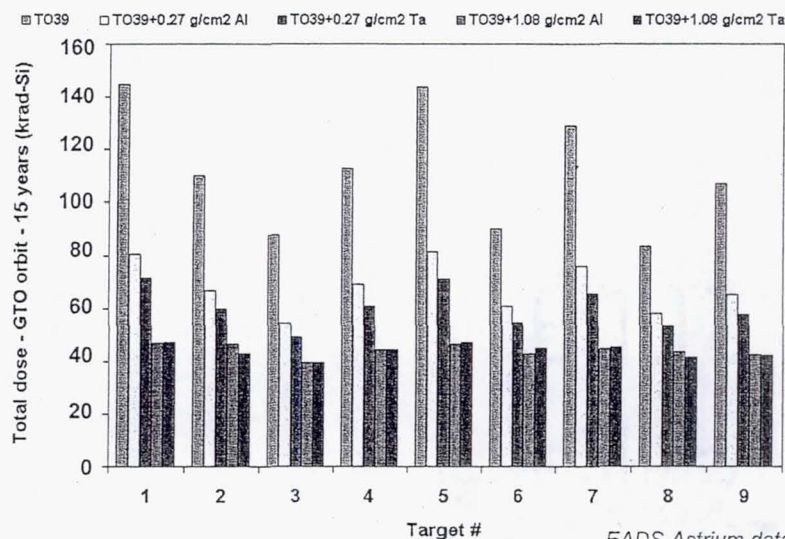
The electronic part packages also provide shielding. This slide shows the 15-year dose levels calculated within 9 locations of a telecommunication satellite's electronic box. The calculations were performed for a geostationary transfer orbit (GTO) and three different types of packages: a metal TO-39 case, a ceramic quad flat package CQFP), and a plastic thin small outline package (TSOP).

We can clearly see the effect of the package on the calculated dose levels for the 9 different locations. The CQFP package provides the largest shielding. However, in the locations where the dose level are the lowest, the package effect is less significant.

Reference:

"Impact des propriétés effectives des matériaux et structures de blindage sur le calcul des niveaux de dose," EADS-Astrium study report, AIN.RA.RM.705102.01, Jan. 2002.

TID mitigation – spot shielding



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If built-in mass on the spacecraft cannot be arranged so as to protect all sensitive components, then some add-on absorber may have to be added. The first aim of add-on shielding is to interpose a few millimeters of any suitable material between the device of interest and the external environment.

If the array of devices to be shielded is small, we can save weight by enclosing the array in a compact shield rather than build the same thickness on to the outside of the electronic box. This is the idea of spot shielding: simply to obtain a given dose reduction in a given volume for the minimum weight penalty.

This slide shows the effect of spot shielding for the TO39 package in the application presented in the previous slide. The dose levels were calculated for two different shielding thickness, 0.27 g/cm² and 1.08 g/cm², and two different shielding materials, Al and Ta.

We can see that adding 0.27 g/cm² of shielding material on top of the device package reduces the dose levels by a factor 1.4 to 2 depending on the location and the shielding material. We can also see that for the same mass of added shielding, the Tantalum shield always gives lower dose levels. This is consistent with the higher shielding efficiency of heavy materials for electron rich environments.

For the largest shielding thickness of 1.08 g/cm², the dose levels are reduced further. We can see that the shielding material does not make any difference. For these shielding thickness all electrons are already stopped and the remaining environment is dominated by protons.

Aluminum: 0.27 g/cm² = 1 mm, 1.08 g/cm² = 4 mm

Tantalum: 0.27 g/cm² = 0.16 mm, 1.08 g/cm² = 0.65 mm

TID mitigation - Examples

- TMS320C25 Texas Instruments – LEO polar
 - TID soft: 3 krad(Si) (functional failure)
 - Duty cycle in the application: 10% on
 - TID tolerance with application duty cycle: 10 krad
The device has operated flawlessly during the mission
- FPGA 1280 ACTEL - GEO
 - TID soft: 3 krad functional at high dose rate.
 - TID at 1 rad/h: ~ 14 krad functional, 50 mA power consumption increase (max design value) after 8 krad.
 - Multilayer shielding: received dose = 4 krad

EADS-Astrium data



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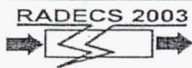
This slide shows two examples of TID mitigation used in space project.

The first one takes advantage of the lower degradation of CMOS devices when they are unbiased.

In the second example the parts were tested at extremely low dose rate. In this condition CMOS parts degrade at a higher dose level when the degradation due to interface states is negligible. In addition a heavy/light material multi-layer shielding was used to reduce the received dose level. This kind of shielding is very efficient in electron dominated environments.

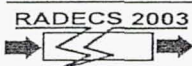
RHA Outline

- Introduction
- Programmatic aspects of RHA
- RHA components
 - requirements and specifications
 - mission radiation environment
 - parts selection and radiation tolerance
- Analysis at the function/subsystem/system level
 - TID/DD
 - SEE
- Conclusion



SEE - Analysis Requirement

SEE LET threshold	Analysis Requirement
$> 100 \text{ MeVcm}^2/\text{mg}$	SEE risk negligible, no further analysis needed
$15 \text{ MeVcm}^2/\text{mg} < \text{LET}_{\text{threshold}} < 100 \text{ MeVcm}^2/\text{mg}$	SEE risk, heavy ion induced SEE rates to be analyzed
$\text{LET}_{\text{threshold}} < 15 \text{ MeVcm}^2/\text{mg}$	SEE risk high, heavy ion and proton induced SEE rates to be analyzed



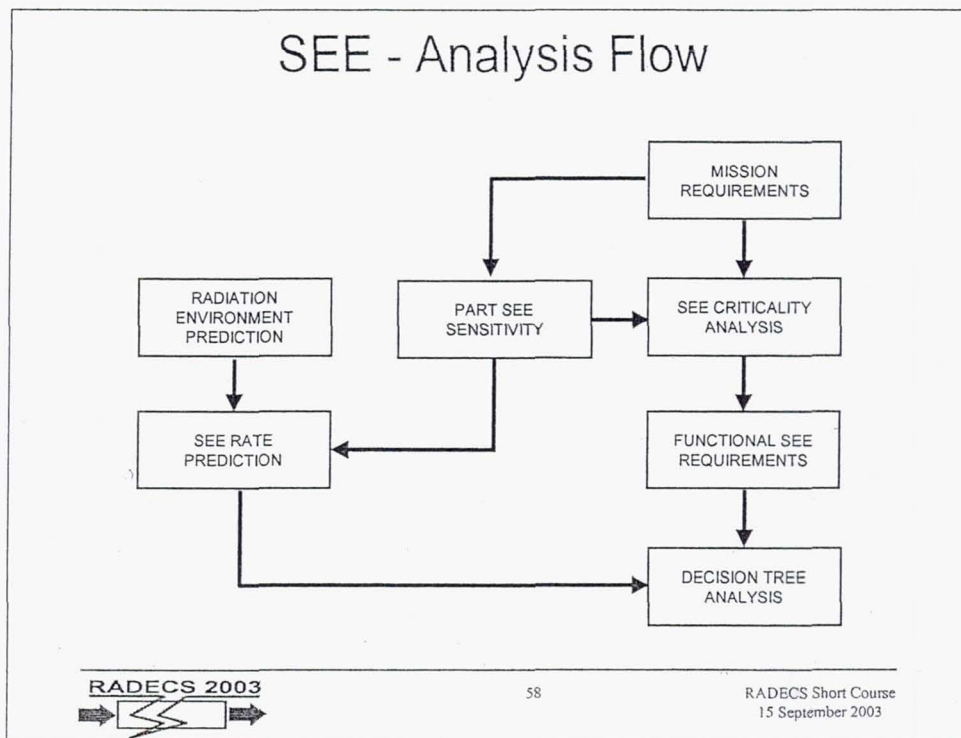
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The SEE analysis is based on the SEE rates calculated for the mission, based on test data. The heavy ion LET threshold, LET_{th} , defines the analysis requirements.

Analysis (SEE rates predictions) must be performed not only for nominal conditions, but worst case operate-through conditions.

SEE are probabilistic events, not long term degradation. The SEE may occur the first day of the mission.



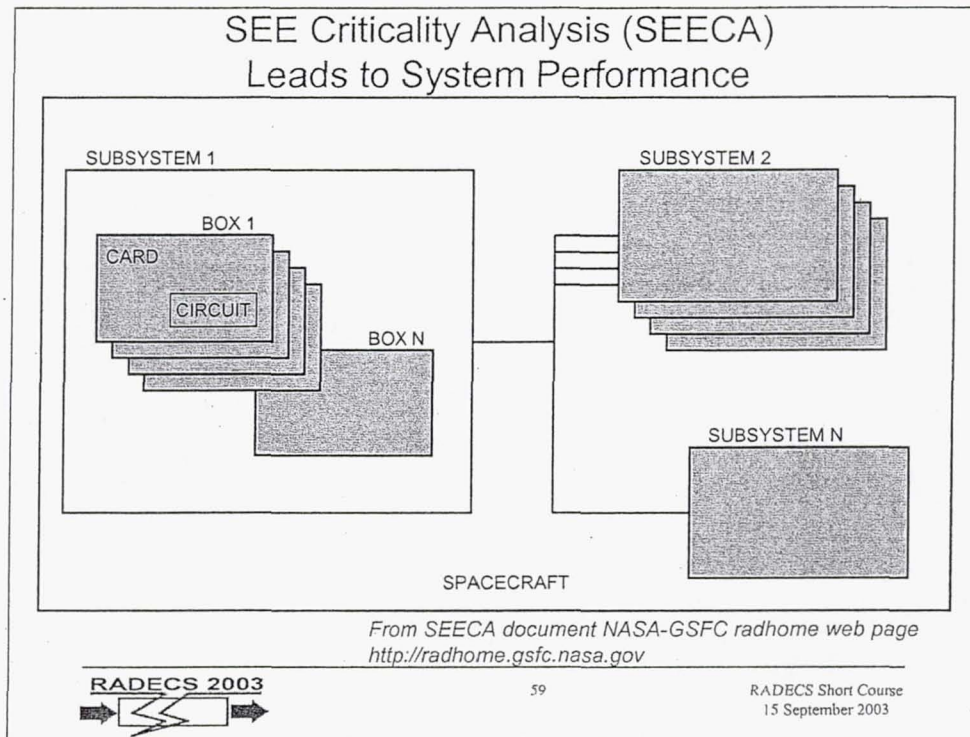
This slide shows the SEE analysis flow chart. The analysis is not direct like for TID and Displacement effects. Not only the part behavior during an event is important, but also the frequency of occurrence of these events: the SEE rates.

SEE is very application specific, this often allows the use of non SEE immune devices in a rational manner.

SEE requirements may alternately be defined by system-level parameters than by piece part requirements. There are two main types of system requirement:

-System availability: for example it might be required that the normal mission operations not be disrupted with an outage requiring ground station intervention more than once a year. And the occurrence of autonomously reset disruptions cannot happen more than once a day.

-Information integrity: in many cases soft errors affect data without altering the systems functions. These errors do not interrupt the flow of information but rather degrades its quality.



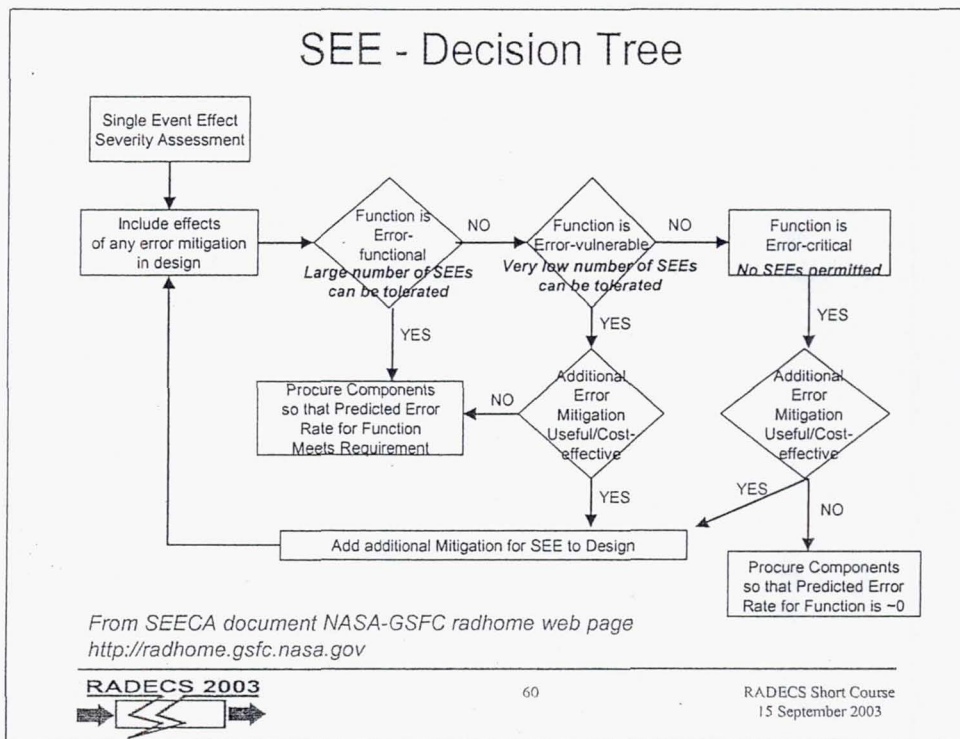
The other part of the SEE analysis is to determine the end effect that an error or failure has on performance of a device, circuit or system. This figure illustrates the criticality analysis at the function level.

The first step is at the device level to define the effect of the SEE on the part in its specific application: improper operation, incorrect device output, incorrect device timing....

Then, the effect is analyzed at the circuit level. For example, a SEU in memory that stores data will cause a bad data point. And an SEU in a memory that contains a program, can cause an improper operation.

If the effect can propagate, it is analyzed at higher level, up to the subsystem and at the system level. At the function level the impact of the different SEE and their propagation through the subsystem and system is analyzed in a similar way than a Failure Mechanism Analysis (FMECA).

When the effect is known, functions are then categorized into criticality classes or category of differing severity of SEE occurrence.



This is a decision tree flow for SEE analysis. We generally consider three classes of criticality:

The highest level of criticality is the error critical level, where no SEE or a very small probability are allowed. The destructive event like SEL are generally in this class. For example a motion controller with a fatal error would be error-critical.

The second class, is the error vulnerable class, where a certain number of errors can be tolerated or mitigated with acceptable performance. For example, a single event effect that disrupt normal operations and requires a ground station intervention to recover functionality may be acceptable if it happens less than once per year. A higher occurrence rate may be acceptable for autonomously reset disruptions.

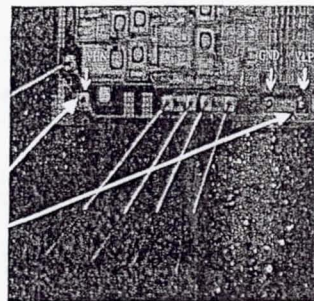
The last class is the error functional class where the function may be unaffected by SEU at the device level, and then parts that have a significant SEE sensitivity can be used. This function immunity to SEE can be due to SEE hardening design like error correction, redundancy. This is for example the case of solid state recorders.

Examples of SEE analysis and SEE mitigation methods are presented in the next section of this document.

Destructive SEE- Mitigation

- Recommendation 1: Do not use devices that exhibit destructive conditions in your environment and application
- Difficulties:
 - May require redundant components/systems
 - Conditions such as low current latchup (SEL) may be difficult to detect
- MANY DESTRUCTIVE CONDITIONS MAY NOT BE MITIGATED
- Mitigation methods
 - Current limiting
 - Current limiting w/autonomous reset
 - Periodic power cycles
 - Device functionality check
- Latent damage is also a grave issue
 - *"Non-destructive" events may be false!*

Vaporized wirebonds
in a Agere LSP2916
MEMS Driver
from an SEL



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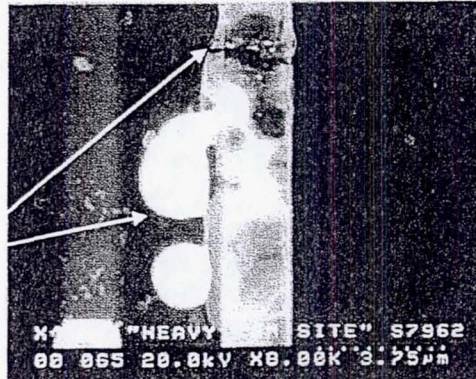
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Destructive SEE conditions may or may not be recoverable depending on the individual device's response. Hardening from the system level is difficult at best, and in most cases not particularly effective. Generally, parts showing a non negligible SEE rate should not be used. On a case-by-case basis use of these parts with adequate circumvention methods could be authorized.

Latent Damage

After T.F. Miyahira, IEEE TNS, vol 48-6, 2001

- SEL events
 - Device may not fail immediately from SEL, but "recover" after a power cycling
- However, in some cases
 - Damage has occurred such as shown here
 - Metal is ejected or cracking has occurred (heat, melt, harden) that may fail catastrophically at some time after event occurrence
 - Reduced reliability/lifetime



SEL test qualification methods need to take latent damage into consideration;

Post-SEL screening techniques required;

Mitigative approaches may not be effective



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A recent JPL study has shown that several types of CMOS devices after non destructive latchup revealed structural changes in interconnects. These changes are due localized ejection of part of the metallization due to metallization melting. These structural damages, called latent damages, do not cause any electrically observable, parametric, or catastrophic device failure but can be detected by surface analysis using optical or scanning electron microscopy, as shown in the picture.

These latent damages represent a possible reliability hazard and they must be considered when testing devices from damage to latchup as well as in establishing limits for current detection and shutdown as a means of latchup protection.

Reference:

H. N. Becker, T. F. Miyahira, A. H. Johnston, " Latent Damage in CMOS Devices From Single-Event Latchup," *IEEE Trans. Nucl. Sci.*, vol. 49, n°6, p.3009, Dec. 2002.

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Conclusion

- The RHA approach on space systems is based on risk management and not on risk avoidance
- RHA process is not confined to the part level
 - Spacecraft layout
 - System/subsystem/circuit design
 - System requirements and system operations
- RHA should be taken into account in the early phases of a program development, including the proposal and feasibility analysis phases

Agencies Specifications-Guidelines

- NASA SEE specification, <http://radhome.gsfc.nasa.gov>
- NASA Single Event Effect Criticality Analysis (SEECA), <http://radhome.gsfc.nasa.gov>, 1996
- NASA Guideline for Optocoupler Ground Radiation Testing and Optocoupler Usage in the Space Radiation Environment, <http://radhome.gsfc.nasa.gov>, 2001
- NASA Guidelines for Single Event Transient (SET) Testing of Linear Devices, <http://radhome.gsfc.nasa.gov>, 2003
- ESA PSS-01-609 Issue 1 The Radiation Design Handbook, <https://escies.org/public/radiation/esa/standards.html>, 1993
- ESA ECSS-Q-60A Space Product Assurance: Electrical, Electronic and Electromechanical (EEE) Components, <https://escies.org/public/radiation/esa/standards.html>, 1996



Reference documents

- "Radiation Requirements and Requirement Flowdown: Single Event Effects (SEEs) and Requirements," K. LaBel, HEART 2003, March 2003
- "Radiation Hardness Assurance for Space Systems," C. Poivey, NSREC2002 short course, July 2002
- "Emerging Radiation Hardness Assurance Issues: A NASA Approach for Space Flight Programs," K. LaBel & al., IEEE Trans. Nucl. Sci. vol.45, n°6, pp. 2727-2736, Dec. 1998
- "Hardness Assurance for Space System Microelectronics," R. Pease & D. Alexander, Radiat. Phys. Chem., Jan. 1994

Other references

- The Effects of Radiation on Electronics Systems, Messenger and Ash, Van Nostrand Reinhold, 1986.
- Handbook of Radiation Effects, Holmes-Siedle and Adams, Oxford Science Pubs, Rev. 2, 2001.

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